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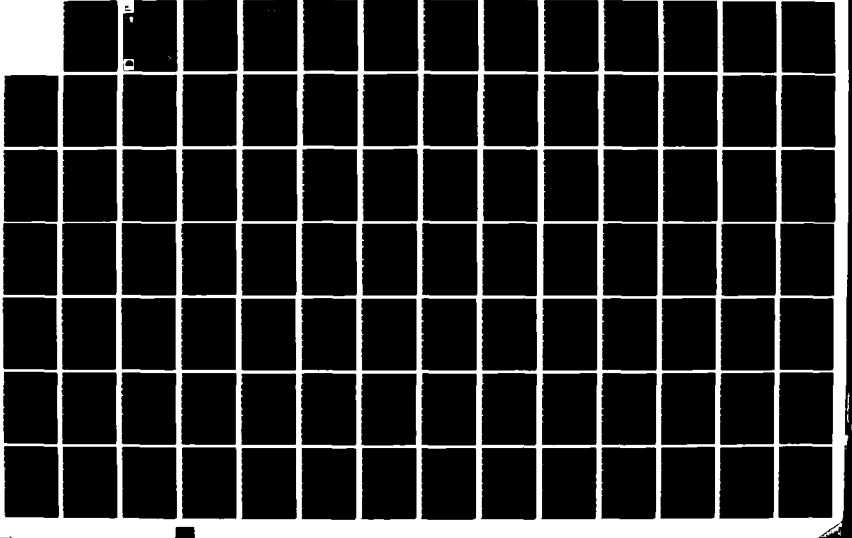

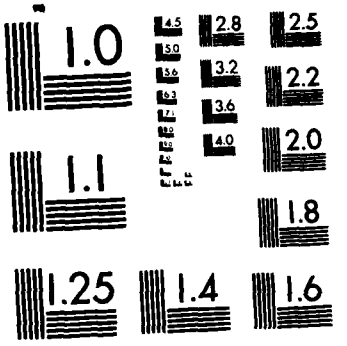

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STRUCTURES LABORATORY

TECHNICAL REPORT SL-85-9

EXPANSIVE GROUT PLUG EFFECTS IN RESTRAINED ENVIRONMENTS

by

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Technology needs to be developed which can assure the safe storage of hazardous waste material in underground cavities. Both analytical techniques and experimental methods will be used in the development of this technology. For instance, finite-element analysis can be used to determine stresses and deformations in the plugging environment. Experimental methods can be used to determine parameters (under the proper environmental conditions) such as the

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properties of the material which forms the cavity, the properties of the plugging material, the relation of pressure and restraint of the plugging material, and the durability of both the host material and the plugging material.

A large portion of this report is devoted to the pressure-versus-restraint relation of the plugging material. This relation can be determined by using steel pipes to provide known restraints on the plugging material as it expands. The pressure-versus-restraint of the expansive material can be determined from pressures obtained from the fluid pressure calibration of the pipes and from later measurements of strains on the pipes due to the presence of the expansive material inside the pipes.

The pressure-versus-restraint relation as demonstrated in tests of BCT-1-FF grout in pipes under conditions of insignificant temperature effects is included only as an illustration of the analysis procedure. In later checking it was found that the data acquisition system used in testing BCT-1-FF probably had baseline or initial voltage changes. After several days, the drift in baseline voltage could have caused the test data to be inaccurate. A new instrumentation system has been implemented to eliminate this problem.

It was found that temperatures between 85° F and 110° F will produce optimum expansion of the BCT-1-FF grout (this was determined by testing the BCT-1-FF grout in glass jars). This can vary somewhat with setting time and strength gain of an expansive mixture.

This report also contains a section which illustrates how average pressures created by grout bar tests can be correlated with the pressures produced in cylindrical containers. Keywords: (7 - p 4)

It is recommended that a range of expansive characteristics be determined for effective stressing and sealing in practical borehole plugging situations. The best expansive material should be determined for these environments, and the causes of extraordinary variations in the expansion of material from the same batch should be determined. The phasing of strength gain and expansive product development should be studied in relation to plug expansion and durability.

It is also recommended that appropriate computer programs be linked together with instructions for a finite-element solution which can iterate to obtain equal strains at the plug-rock interface from the pressure-versus-restraint relation and the finite-element solution, and thus obtain stress fields in any environment.

Stress in physical situations may affect index properties such as permeability, compressive and tensile strengths, durability, etc., reflected by test results which are determined for unstressed specimens. For example, it has been established that stress promotes deterioration of concrete in a freezing and thawing environment. It is suggested that tests be conducted to determine whether realistic stress conditions affect short- and long-term properties which are used in evaluating the safety of borehole plugging situations.

PREFACE

This investigation was performed in the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES).

The report was prepared by Dr. Carl E. Pace of the Research Group, Concrete Technology Division (CTD), and Mr. C. W. Gulick of Sandia National Laboratories. Messrs. John A. Boa, Jr., and Donald M. Walley assisted in conducting the tests.

Dr. Avi Singhal, Professor and Director of the Earthquake Research Laboratory at Arizona State University and currently working in the SL at WES, reviewed the analytical equations and experimental data and made significant comments.

The study was conducted under the general supervision of Messrs. Bryant Mather, Chief, SL; J. T. Ballard, Assistant Chief, SL; and J. M. Scanlon, Chief, CTD, SL.

COL Allen F. Grum, USA, was Director of WES during the preparation and publication of this report. Dr. Robert W. Whalin was Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic millimetres
inches	0.0254	metres
inches per pound, force	0.00571015	metres per newton
microinches per inch	0.0254	micrometres per metre
pounds (force)	4.448222	newtons
pounds (force) per inch	175.1268	newtons per metre
pounds (force) per square inch	0.006894757	megapascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

EXPANSIVE GROUT PLUG EFFECTS IN RESTRAINED ENVIRONMENTS

PART I: INTRODUCTION

Background

1. In a number of places, such as in the Netherlands, underground cavities in salt are being used for the disposal of chemical and industrial waste materials. There are formations of salt and other materials in the United States in which cavities might play a role in the storage of hazardous waste materials. Since 1975, the US Army Engineer Waterways Experiment Station (WES) has been involved in the development and evaluation of pumpable grouts for the plugging and sealing program in support of the Waste Isolation Pilot Plant (WIPP). Much literature on this subject is available and is referenced in the Bibliography at the conclusion of this report. The WIPP facility is planned for location in bedded salt approximately 2,150 ft* below the surface in southeast New Mexico. With adequate study and technological preparation, appropriate hazardous waste storage procedures can be provided.

2. Technological studies require a knowledge of the mechanical and physical properties of both the material in which the cavity is formed and the material which will seal the access to the cavity. If an expansive grout plug is used for sealing purposes, it is important that the rock in which the grout plug has been placed is not harmfully cracked or damaged by the expanding plug. It is also important that pressure be permanently maintained against the sides of the cavity so that effective sealing will result. The interaction between the sealing plug and the cavity can be determined analytically if the properties of the plug and cavity material are known.

3. For the purpose of this study, the rock environment is assumed to be axisymmetric in its geometric properties for all closed-form considerations. If the environment is not axisymmetric, a finite-element solution can be obtained for an environment of any shape.

4. Ideally, the expansive behavior of the grout plug and the deformation and expansive properties of the rock environment should result in equal

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

deflections at the interface between the host rock and the grout plug. If a gap exists between the host rock and the expansive plug, no pressure will be exerted and erroneous results will be obtained unless a finite-element analysis is developed to accurately model the development of the gap.

5. In actual practice, when a material such as an expansive grout produced by hydraulic cement is emplaced in a restrained volume, the volumetric interaction with the surroundings will be such that the deflection at their interface is equal during the time when (a) the temperature is increasing and at the interface between host material and plug, the host material is expanding less due to temperature change than the plug, (b) there is no negative length change or contraction of the plug produced by cooling, moisture loss, endothermic reactions, or chemical reactions which cause the formation of products of lower density, and (c) the decrease in the compressive elastic strain in the surroundings at the plug-rock interface does not become less than the negative strain of the interface of the expansive plug as the heat of hydration decreases.

6. Determination of stress field development in the rock environment requires that the pressure-versus-restraint properties of the grout and the deformation properties of the rock environment be known. With these properties known, the solution to the expansive grout stressing effects in a rock environment can be determined analytically. This report does not consider details of the interaction between the grout plug and the rock environment, such as temperature variations (especially from the heat of hydration when the plug is poured). This will be done later in the solution of practical or typical problems.

7. The overall solution to the borehole plugging problem is determined by using the pressure-versus-restraint curves of the plugging material and the material properties of the cavity material in a finite-element analysis. This overall solution is logically constructed for obtaining the solutions to practical or typical problems.

Objectives

8. The objectives of this study are to:

   a. Develop an experimental method for determining the expansive properties of a grout mixture in a cylindrical environment.

   b. Correlate expansive grout properties obtained from tests in

cylindrical restrained environments with data from restrained and unrestrained grout bar tests.

c. Generally develop analytical concepts for determining the stress and deformation fields in a plugged environment.

9. Bar tests have been conducted by WES for many years, and over the years a large collection of grout bar data has been obtained. The correlation of expansive grout properties in cylindrical environments with data from grout bar tests will allow the estimation of pressure from grout bar tests. Therefore, it would be advantageous if the existing grout bar data could be used to estimate expansion pressure.

Scope

10. The general method for determining the expansive properties of a given grout and the method for determining the stresses produced by an expanding grout in a rock environment will be established.

PART II: GROUT PRESSURE VERSUS RESTRAINT

Pressure Versus Restraint in Cylindrical Environments

11. The objective of this part is to develop an experimental method by which the expansive properties of a given grout mixture can be defined and used to determine the stress field and stress concentrations induced in a surrounding environment. This portion of the report also examines the relationship between the 14-day pressure exerted by a particular expansive grout (BCT-1-FF), data on which are given in Table 1, and the restraint of any environment. After a few days, the data acquisition system probably began to have a drift of baseline voltage, causing error in the measured data. This conclusion was reached from later testing and analysis. This problem has been corrected and the data which are presented in the report are used only to illustrate the analysis procedure.

12. The pressure- (maxima in this study) versus-restraint relation can be used in analytical computations to determine the stress field created in the material surrounding an expansive grout plug. From the strength and deformation properties of the surrounding material and the imposed stress fields, decisions can be made concerning possible cracking or detrimental effects of excessive permeability, material damage, and/or deterioration. For an effective seal to be permanently maintained at the interface of an expanding grout plug and a host material (rock), the positive compressive force of the expansion must be maintained, to some degree, on the surroundings. For such force to be permanently maintained, it is necessary that the elastic strain manifested by the surrounding rock due to the force exerted by the plug exceed the subsequent cooling contraction plus drying shrinkage of the plug with respect to the surroundings. It is, however, important to have evidence that the required elastic-compressive strain level of the rock will be of sufficient magnitude without undergoing damaging crushing.

13. Expansive plugs can be engineered for effectiveness by analyzing the effects of specific mixture proportions and selecting the mixture which is most effective for the particular rock environment. The pressure-versus-restraint relation of expansive grouts depends, among many other factors, upon the constituents of the mixture. The constituents of the mixture can be varied to cause different expansive characteristics for a particular rock and

environment. In this way, a grout or concrete can be selected to have properties which are required for effective sealing or stressing in a particular environment. The objective of this study is not to examine a variety of expansive grout mixtures and determine their expansive characteristics. Instead, a test was envisioned which would permit a determination of the pressure-versus-restraint relation for an expansive mixture.

14. Steel cylinders with various inside diameters and wall thicknesses (causing varying degrees of restraint) were used to contain the expanding BCT-1-FF grout. If the pressure in each cylinder (caused by expanding grout) could be determined, the grout pressure versus restraint could then be obtained. The pressure exerted by the expanding grout can be determined from a fluid-pressure calibration of each cylinder. The calibration was obtained using the following procedure:

a. Select steel pipe (Figure 1) of varying wall thickness, inside diameter, and length. The length of each piece of pipe should be sufficient so that the strain gage reading at the midlength of the pipe will not be affected by end conditions. This requirement is met if the length of the piece of pipe is at least 2-1/2 times its inside diameter.

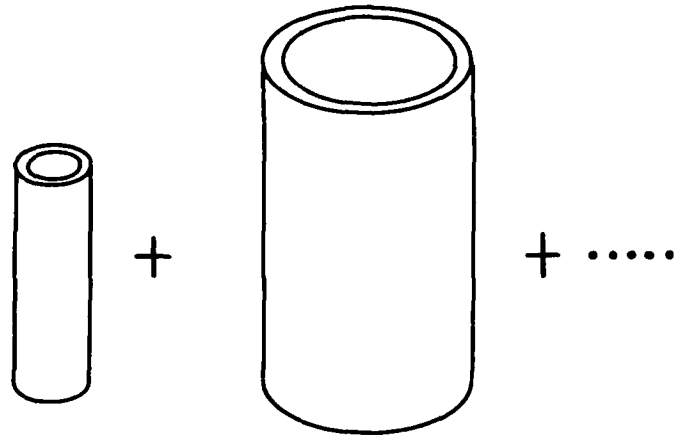


Figure 1. Steel pipe of varying wall thickness, inside diameter, and length

b. Cap both ends of each piece of pipe and provide a threaded pipe in one cap of each pipe for access to calibrate the cylinder by internal fluid pressure.

c. Place and cure a pair of both radial and longitudinal strain gages 180 deg apart on the outside center of each pipe.

d. Fill each pipe with fluid and, through the threaded pipe connection, gradually increase the pressure acting on the inside of the pipe. At the same time, record strain measurements.

This will give data from which pressure-strain curves can be obtained (Figure 2). The pressure inside the pipe for measured strains is known at the center and on the outside of the pipe; therefore, a calibration curve for the pipe can be constructed. The grout will be placed in the same pipe and as it expands inside the pipe, the same strain gages will be read. The calibration curves and the physical dimensions of the pipe can be used to obtain the pressure being exerted by the grout.

e. Use the maximum experimental grout pressures and strains and the calibration curves for each pipe to obtain a pressure-versus-restraint curve for a given mixture and environmental condition (Figure 3). Expansion and probably other aspects of plug performance may depend on the relationship of the phasing of strength gain and expansive product formations.

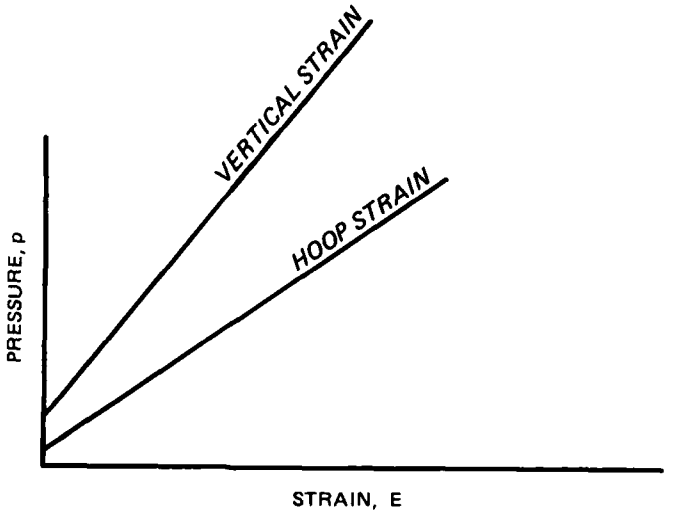


Figure 2. Calibration curves for one steel cylinder

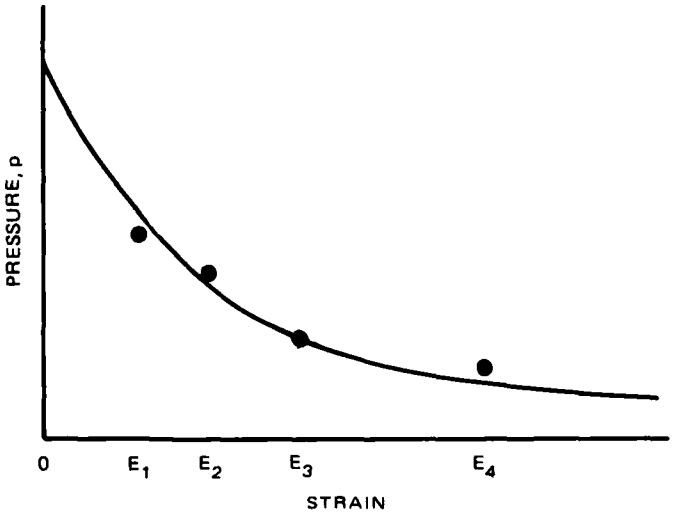


Figure 3. Pressure restraint curve for grout

15. The physical dimensions of the cylinders are presented in Table 2. The calibrations for the cylinders are presented in Appendix A. The calibrations are for a closed-end cylinder which is pressurized by a fluid. The radial pressure expands the cylinder, causing tangential strains and stresses. For sections well removed from the ends of the cylinder, the fluid pressure against the ends of the cylinder should cause an approximately uniform or uniformly varying longitudinal strain across the cylinder cross section. Thick-wall cylinder formulas give the best results for stresses and strains in or on the cylinder.

16. The calibration data are not directly applicable to the test data because the loading of the cylinder is different. The main concepts concerning the pipe calibrations and the expansive grout tests are as follows:

a. The type of loading which would occur in fluid calibration is illustrated in Figure 4. The fluid calibration exerts the same pressure in all directions (hydrostatic pressure is neglected). Hoop strains are produced by the radial pressures. Longitudinal strains are produced by internal pressure, p ,* on the ends of the cylinder. The Poisson's effect causes an interaction between hoop and longitudinal strains.

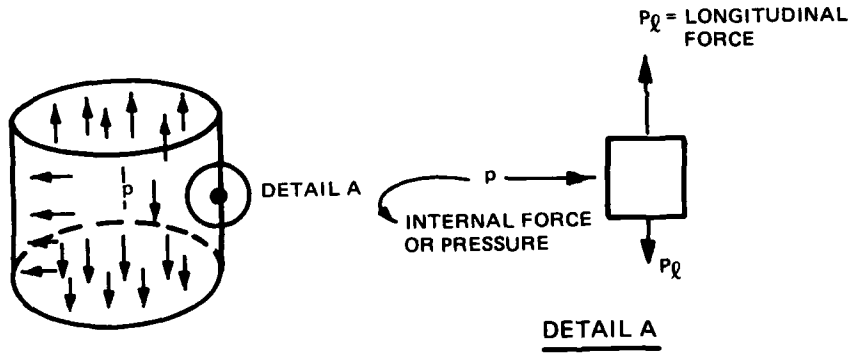


Figure 4. Loading concept for fluid calibration of cylinder

b. The loading concept for the cylinder filled with expanding grout is illustrated in Figure 5. In this case, the cylinder has an open end and has radial pressures, arching pressures, and longitudinal frictional stresses due to vertical expansion. The radial pressures will create strains like those which were developed in the fluid pressure situation. The arching pressure will have a radial pressure component and a longitudinal component which causes a longitudinal frictional

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix F).

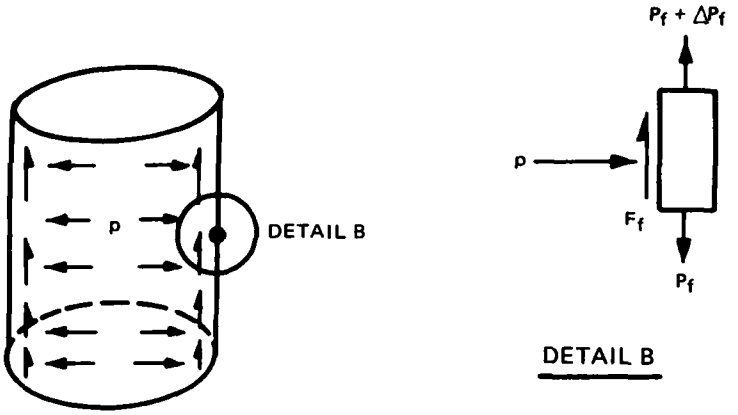


Figure 5. Loading concept for cylinder with expanding grout

force on the inside face of the cylinder. Before the calibration is applied to the data, the tangential strains must be increased or decreased for the longitudinal strain effects which are more or less than those produced by the fluid pressure situation in order that the fluid pressure calibrations will give accurate results. It is assumed that the frictional stress effect at a given section of the cylinder will produce the same longitudinal stress or strain distribution in the cylinder walls as the longitudinal stress or strain produced by the fluid pressure calibration.

c. A correction of strains from the outside face of the cylinder wall to the face of the grout plug is not necessary when calculating pressures exerted by the grout because the strains are measured on the outside of the cylinder for both the calibration and the test. It will be necessary to use strains corrected to the grout-cylinder interface for correlation purposes.

17. As grout expands in a cylinder, the hoop strains which occur are entirely due to radial and longitudinal pressure against the inner surface of the cylinder. The hoop strains consist of two components; radial pressures from the radial expansion and a radial component of arching pressure. The vertical expansion plus the vertical component of arching will be resisted by the angle of internal friction at the pipe and grout interface, and this will load the pipe in a vertical direction, producing longitudinal strains. These longitudinal strains will vary along the pipe length but the longitudinal strain at the center of the pipe (gage location) can be used to make

corrections to the hoop strains due to the Poisson's effect. That is, the equations of stresses and strains at a point will be valid for the longitudinal and hoop strains at the gage location. The greater the longitudinal forces on the cylinder walls (assuming the frictional resistance is adequate to prevent slip), the greater will be the longitudinal strains.

18. The longitudinal strains at a section of the cylinder are produced by frictional forces which increase from the closed end of the cylinder upward toward the open end of the cylinder. Even though the frictional forces are on the inside of the cylinder walls, they develop along the entire length of the cylinder. Because these frictional forces develop from the bottom to the top of the cylinder, they will be distributed somewhat uniformly across the cylindrical wall cross section.

19. The grout was placed in the cylinders, and the resulting tangential and longitudinal strains were measured. The tangential and longitudinal strain data are presented in Appendix B. The calibration data were used to convert the strains to pressures. The pressure-time data for the hoop strains are presented in Appendix C. Corrections due to more or less frictional effects than those produced by the fluid pressure situation are not made in these plots but will be made to maximum hoop strains before correlation plots are determined. The pressures for longitudinal strains are presented in Appendix D, but do not correspond to the fluid pressure calibration from which they were obtained and are presented for interest and not to imply what pressures the expansive grout created. The temperature-versus-time data are presented in Appendix E. The strains from the longitudinal or vertical gages will be used to determine the degree of longitudinal strain put on the cylinder walls from the frictional forces in comparison to the longitudinal strains in the fluid pressure calibration situation.

20. The maximum expansive cementitious pressures as determined from the tangential or hoop strains will be used to develop the relation between internal pressures and restraint. The restraint of the various cylinders will be defined as the slope of the cylinder calibration psi/(in./in.) . The restraint relations are developed later in this part of the report. The restraint values based on hoop strains are presented in Table 3. The hoop strains for a pressurized open-end cylinder and a closed-end cylinder are presented in Equations 1 and 2. These are classical equations and their derivations are presented in many textbooks. The hoop strain equation for the

open-end cylinder neglects pressure that exists on the ends of the closed-end cylinder.

$$\varepsilon_{max_{hoop}}\text{(open ends)} = \left\{ \frac{p_1}{E} \left[\frac{r_2^2 + r_1^2 + \mu\left(r_2^2 - r_1^2\right)}{r_2^2 - r_1^2} \right] \right\} \tag{1}$$

$$\varepsilon_{max_{hoop}}\text{(closed ends)} = \frac{p_1}{E} \left[\frac{r_2^2 + (1 - \mu)r_1^2 + \mu\left(r_2^2 - r_1^2\right)}{r_2^2 - r_1^2} \right] \tag{2}$$

The ratio of $\left[\varepsilon_{max_{hoop}}\text{(open ends)} \Big/ \varepsilon_{max_{hoop}}\text{(closed ends)}\right]$ gives the effect of longitudinal strain on maximum hoop strain for closed-end cylinders pressurized by a fluid. This ratio is

$$\frac{\varepsilon_{max_{hoop}}\text{(open ends)}}{\varepsilon_{max_{hoop}}\text{(closed ends)}} = \frac{r_2^2 + r_1^2 + \mu\left(r_2^2 - r_1^2\right)}{r_2^2 + (1 - \mu)r_1^2 + \mu\left(r_2^2 - r_1^2\right)}$$

The values of this ratio are presented in Table 3. The maximum values of hoop and longitudinal strains from the test of expansive grout are also presented in Table 3. The maximum hoop strains will be adjusted and maximum pressures calculated.

21. In order to use the fluid pressure calibration curves, maximum hoop strains from the expansive grout test must be adjusted for longitudinal force created in the cylinder walls versus longitudinal force associated with maximum hoop strains in the fluid pressure situation. Equivalent fluid pressure conditions will be the basis for pressure-versus-restraint correlation plots.

22. The maximum hoop strains will be used in the calibration equations for the hoop strains

$$p = M_1\varepsilon_{hoop} + B_1 \tag{3}$$

$$p = M_2\varepsilon_{longitudinal} + B_2 \tag{4}$$

to calculate the associated ε_ℓ'' (longitudinal strain for equivalent fluid pressure situation) for the maximum $\varepsilon_h(\varepsilon_{hoop})$ from the test data. Since for a given cylinder, p is the same for each of Equations 3 and 4,

$$\varepsilon''_{\ell} = \frac{M_1 \varepsilon_t + B_1 - B_2}{M_2} \tag{5}$$

The ε''_{ℓ} values associated with the maximum measured hoop strains for a fluid pressure situation are calculated from Equation 5 and are given in Table 4.

23. The maximum measured ε_{ℓ} values are given in Tables 3 and 4. The measured longitudinal strains divided by the calculated equivalent fluid pressure longitudinal strains (ε''_{ℓ}) will give the multiple of the longitudinal strains developed in relation to a fluid pressure situation. One correction must be made before the ratio of measured longitudinal strains and associated longitudinal fluid pressure strains can be used to correct the test data to an equivalent fluid pressure situation. Some ε_{ℓ} or ε_h calibration curves do not go through zero; therefore, the ratio of strains must be that of total strains from $p = 0$ at $\varepsilon = 0$ or the computations using theoretical equations and obtaining correlation plots can become distorted.

24. The corrections to the calculated fluid pressure strains and the measured strains are calculated and the corrected strains are presented in Table 4. The ratio of $\varepsilon_{\ell_{measured}} / \varepsilon''_{\ell_{fluid\ pressure}}$ is also presented in Table 4. The hoop stresses are corrected to an equivalent fluid pressure situation by the following equation.

$$\varepsilon_{h_{corrected}} = \varepsilon_{h_{measured}} + \varepsilon_{h_{measured}} \left[\left(\frac{\varepsilon_{max_{hoop}}\ (open\ ends)}{\varepsilon_{max_{hoop}}\ (closed\ ends)} - 1 \right) \left(\frac{\varepsilon_{\ell_{measured}}}{\varepsilon''_{\ell_{fluid\ pressure}}} - 1 \right) \right] \tag{6}$$

25. The effect of the longitudinal strain (ε_{ℓ}) on the hoop strain (ε_h) for the fluid pressure condition is represented by

$$\left(\frac{\varepsilon_{max_{hoop}}\ (open\ ends)}{\varepsilon_{max_{hoop}}\ (closed\ ends)} - 1 \right)$$

The effect of the difference between measured longitudinal strain and the longitudinal strain which occurs in the fluid pressure situation is represented by the following factor.

$$\frac{\varepsilon_{\ell_{measured}}}{\varepsilon''_{\ell_{fluid\ pressure}}} - 1$$

26. The maximum pressures exerted by the grout (based on the grout creating a longitudinal stress in the cylinder equivalent to the fluid pressure situation) are then calculated and are presented in Table 4.

27. The interface circumferential strains are the strains which are needed for correlation purposes. It is the ε_h at the interface of the grout and cylinder which is significant; the cylinder is just a vehicle of constraint and its wall thickness is of no significance other than to produce restraint. The correction to the cylinder-grout interface is derived as shown in Figure 6.

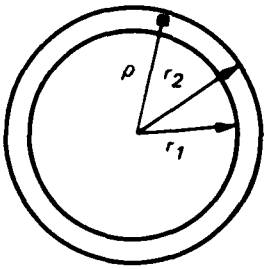


Figure 6. Correction to cylinder-grout interface.

$$\varepsilon_{h_{r_1}} = \frac{2\pi(r_1 + \Delta r) - 2\pi r_1}{2\pi(r_1)} = \frac{\Delta r}{r_1}$$

$$\varepsilon_{h_{r_2}} = \frac{2\pi(r_2 + \Delta r) - 2\pi r_2}{2\pi(r_2)} = \frac{\Delta r}{r_2}$$

$$\frac{\varepsilon_{h_{r_1}}}{\varepsilon_{h_{r_2}}} = \frac{\frac{\Delta r}{r_1}}{\frac{\Delta r}{r_2}} = \frac{r_2}{r_1} \tag{7}$$

$$\varepsilon_{h_{r_1}} = \varepsilon_{h_{r_2}} \frac{r_2}{r_1}$$

28. The maximum pressures created by the grout at the grout-cylinder interface are calculated and are then correlated. Many correlations were investigated considering elasticity theory, pressurized cylinder theory, dimensionless parameters, and the physical situation.

29. Several developments help determine the parameters to use for correlation plots. One such development is the derivation showing that the diameter of cylindrical cavities of constant restraints does not have any influence on the pressure which is exerted against the cavity walls. This derivation is presented below. The general situation of expansive plug in an infinite rock environment is presented in Figures 7, 8, and 9.

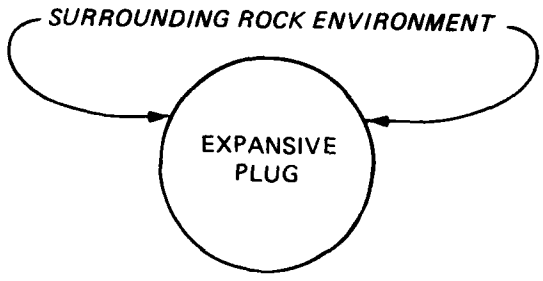


Figure 7. Plan view of expansive plug and infinite rock environment

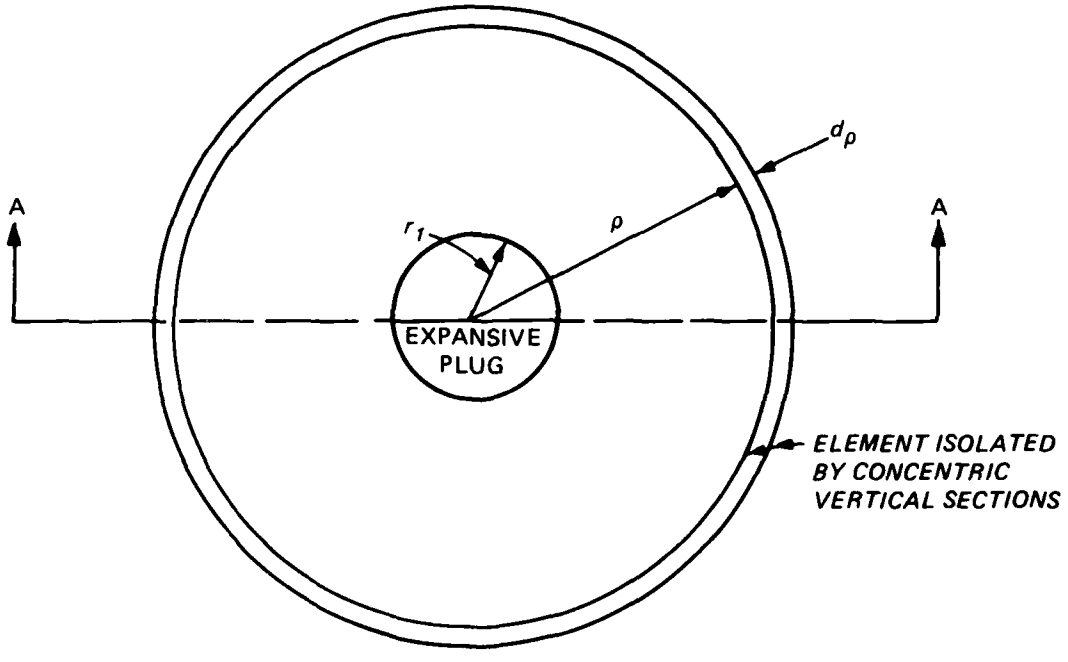


Figure 8. Isolated thin-wall cylinder in rock environment

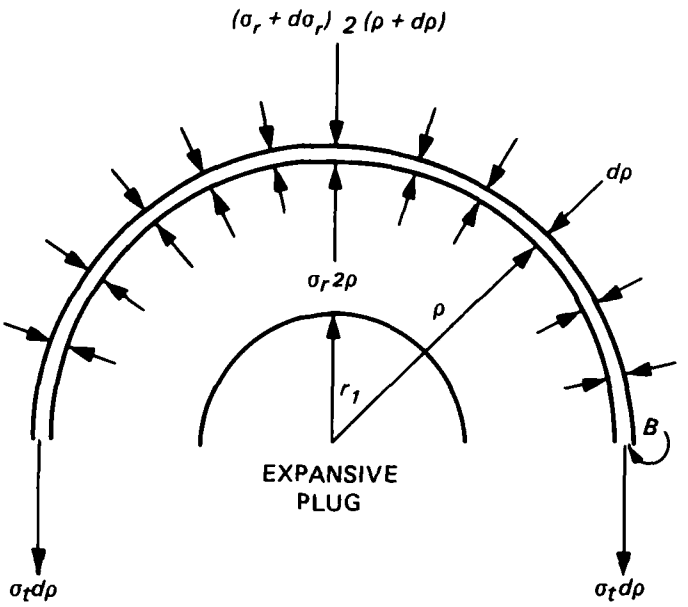


Figure 9. Section A-A

30. Sum vertical forces and obtain

$$2\sigma_t d\rho = 2\rho\sigma_r - (\sigma_r + d\sigma_r)2(\rho + d\rho)$$

$$2\sigma_t d\rho = 2\rho\sigma_r - 2\rho\sigma_r - 2\sigma_r d\rho - 2\rho d\sigma_r - 2d\sigma_r d\rho$$

Since $2d\sigma_r d\rho$ is negligible in relation to the other terms, the equation reduces to

$$\sigma_t = -\sigma_r - \rho\left(\frac{d\sigma_r}{d\rho}\right) \tag{8}$$

31. For the present, assume that there is only radial expansion of the expansive plug and that the longitudinal stresses are zero. The interface pressure will be derived using the following well-known equations for stress and strain.

$$\epsilon_\ell = \frac{\sigma_\ell}{E} - \frac{\mu\sigma_t}{E} - \mu\frac{\sigma_r}{E} \tag{9}$$

$$\varepsilon_t = \frac{\sigma_t}{E} - \frac{\mu\sigma_r}{E} - \frac{\mu\sigma_\ell}{E} \tag{10}$$

$$\varepsilon_r = \frac{\sigma_r}{E} - \frac{\mu\sigma_\ell}{E} - \frac{\mu\sigma_t}{E} \tag{11}$$

Equation 8 becomes

$$\varepsilon_\ell = -\mu \frac{\sigma_t}{E} + \mu \frac{\sigma_r}{E} \tag{12}$$

Since ε_ℓ , μ , and E are constants $\left(\text{let } 2\alpha = -\frac{\varepsilon_\ell E}{\mu}\right)$, we have

$$\sigma_t - \sigma_r = -\frac{\varepsilon_\ell E}{\mu} = 2\alpha \tag{13}$$

From Equations 8 and 13,

$$2\alpha = -2\sigma_r - \rho \frac{d\sigma_r}{d\rho}$$

or

$$\frac{d\left(\rho^2\sigma_r\right)}{d\rho} = -2\alpha\rho \tag{14}$$

When integrated, Equation 13 becomes

$$\rho^2\sigma_r = -\alpha\rho^2 + \beta \tag{15}$$

where β is a constant of integration. Rearranging Equation 15 obtains

$$\sigma_r = \frac{\beta}{\rho^2} - \alpha \tag{16}$$

Equations 12 and 15 give

$$\sigma_t = \frac{\beta}{\rho^2} + \alpha \tag{17}$$

For $\sigma_r = p_1$ at $\rho = r_1$ and $\sigma_r = 0$ at $\rho = r_2$,

$$p_1 = \frac{\beta}{r_1^2} - \alpha$$

and

$$0 = \frac{\beta}{r_2^2} - \alpha$$

Therefore,

$$p_1 = \frac{\beta}{r_1^2} - \frac{\beta}{r_2^2} = \frac{r_2^2\beta - r_1^2\beta}{r_1^2 r_2^2}$$

from which

$$\beta = \frac{p_1 r_1^2 r_2^2}{r_2^2 - r_1^2} \tag{18}$$

and

$$\alpha = \frac{p_1 r_1^2}{r_2^2 - r_1^2} \tag{19}$$

From Equations 17, 18, and 19,

$$\sigma_t = \frac{p_1 r_1^2 r_2^2}{r_1^2\left(r_2^2 - r_1^2\right)} + \frac{p_1 r_1^2}{r_2^2 - r_1^2} = \frac{p_1\left(r_2^2 + r_1^2\right)}{r_2^2 - r_1^2} \tag{20}$$

This is the maximum value of σ_t since the maximum value of σ_t will occur at the inner surface where ρ has its minimum value r_1. From the equation of strain (Equation 10), ε_t becomes

$$\varepsilon_t = \frac{1}{E}\left(\sigma_t - \mu\sigma_r\right) \tag{21}$$

The change in length of the circumference of the circle whose radius is ρ is $2\pi\rho\varepsilon_t$ and is equal to the summation of the deflection of each point on the circle $2\pi\Delta_B$.

$$\Delta_B = \frac{\rho(\sigma_t - \mu\sigma_r)}{E} \tag{22}$$

Substituting Equation 20 into Equation 22 with $\sigma_r = -p_1$ and $\rho = r_1$, we obtain

$$\Delta_B = \frac{p_1 r_1}{E}\left(\frac{r_2^2 + r_1^2}{r_2^2 - r_1^2} + \mu\right) \tag{23}$$

Assume $r_2 = \infty$, and obtain the limit of $r_2^2 + r_1^2 / r_2^2 - r_1^2$ as $r_2 \to \infty$. This gives the radial deflection in a cylindrical environment for a specific restraining material of infinite extent.

$$\lim_{r_2 \to \infty} \frac{r_2^2 + r_1^2}{r_2^2 + r_1^2} = \lim_{r_2 \to \infty} \frac{1 + \frac{r_1^2}{r_2^2}}{1 + \frac{r_1^2}{r_2^2}} = 1$$

$$\Delta_B = \frac{p_1 r_1}{E}(1 + \mu)$$

since

$$\varepsilon_t = \frac{\Delta_B}{r_1}$$

$$\varepsilon_t r_1 = \frac{p_1 r_1}{E}(1 + \mu)$$

rearranging

$$\varepsilon_t = \frac{p_1}{E}(1 + \mu)$$

solving for p_1

$$p_1 = \frac{\varepsilon_t E}{1 + \mu} \tag{24}$$

This shows that for environments of only radial plug expansion and for the same restraint (that is, for a specific p_1, the same ε_t is produced) the internal pressure is not dependent on the diameter of the expansive plug.

32. If p_1/ε_t does not remain constant, the restraint, and hence p_1, varies with plug diameter. When the diameter and thickness of pipes vary such that the p_1/ε_t or restraint of the pipes are the same, the pressure created in the pipes by an expansive material will be the same. In a given field material, the p_1/ε_t ratio will vary with plug diameter; therefore, the pressure created by an expansive material will vary with plug diameter.

33. The second development establishes relations between test results from expansive bar tests, expansion of material in steel pipes, and expansion in a restrained field environment. This development is made to assure that the definition of restraint for the three situations is consistent.

34. An expansive material can be restrained in various ways. Three ways which have been used are:

a. Formation of bars of the expansive material with a restraining rod connected to end plates running down the center of each bar.

b. Casting of the expansive material in calibrated steel pipes of various restraints.

c. Placement in boreholes or shafts in a field environment.

The first two methods are used as laboratory methods to obtain the expansive property of a material. The final product of the study of an expansive material will be to seal a borehole in the field to protect the environment from hazardous waste products.

35. It is important to have the restraint calculations from each of the three environments consistent. That is, one numerical value of restraint will represent the same restraint in any of the three environments. The following ideas will develop a consistent definition of restraint in the three environments.

36. The relationships which will be developed between the results of expansive bar tests and the results from the test of expansive material in steel pipes are:

a. The restraint of the grout bar and the restraint of the pipe environment will be developed such that they are consistent and have the same numerical meaning in each environment of a given restraint.

b. The effective pressure exerted on the end plates by the grout bar will be predicted from the pressure-versus-restraint curve developed from test results of the expansive material in steel pipes.

37. From pipe test results, a correlation plot will be determined which relates the pressure in the pipe to the restraint of the environment. For consistent definitions of restraint, the pressure-versus-restraint relationship developed from pipe tests will be general and will apply to any restraining environment which is subjected to the same environmental conditions as those for the expansive specimens in steel pipes.

38. The grout bar with a restraining rod in its center and rigidly connected to end plates will be elongated by the expanding grout bar. The concepts of effective pressure exerted by the grout bar and grout bar restraint will be logically developed. The elongation will be produced by the expansive grout interlock and bond with the steel rod and the pressures the grout bar exerts against the end plates. Because a piece of the same rod which was used as the restraint in the grout bar was pulled in a test machine and the force-versus-strain curve for the steel restraining rod was obtained, an effective pressure against the end plates can be computed.

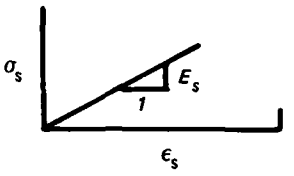
39. At a particular time, the elongation (Δ_B) of the restrained grout bar and hence the strain (ε_B) can be obtained. The strain (ε_B) can be used to obtain the force in the restraining rod from the experimental test results of the force-versus-strain of the restraining rod. The effective pressure for the grout bar is the restraining force (P_B) of the grout bar divided by the area of the grout bar. Initially one may consider that the restraint of the grout bar is the modulus of elasticity (E) or stiffness of the restraining rod. However, review indicates that steel restraining rods have the same stiffness

$$E_{Steel} = \frac{\sigma_{Steel\ rod}}{\varepsilon_{Steel\ rod}}$$

for all size rods, but the restraint of various size rods is different. For example, the restraint of the 1/8-in.-diam rod is of less magnitude than that of the 1/4-in.-diam rod; therefore, a different definition of the restraint must be used for the grout bar.

40. The restraint, measured elongation, and strain occur along the length of the grout bar. From statics the force on any section of the bar is the same; therefore, the restraint on any length of the bar is the same. The restraint then should not depend on the bar length. The restraint of the

grout bar is then defined as the modulus of elasticity of the grout bar.



$$E_s = \frac{\sigma_s}{\epsilon_s}$$

$$\Delta_B = \frac{P_B L_B}{A_B E_B} \tag{25}$$

or

$$E_B = \frac{P_B L_B}{A_B \Delta_B} = \frac{\sigma_B}{\epsilon_B} \tag{26}$$

where

$\Delta_s = \Delta_B$ = total deflection of steel restraining rod or grout bar

$P_s = P_B$ = total load in steel restraining rod or grout bar

$L_s = L_B$ = total length of steel restraining rod or grout bar

A_B = area of grout bar

E_B = modulus of elasticity of grout bar for a particular load or strain level (may be thought of as the modulus of stiffness of the grout bar)

σ_B = stress in grout bar

$\epsilon_s = \epsilon_B$ = strain in steel restraining rod or grout bar

41. The same approach will be used to obtain a consistent definition of restraint of a steel cylinder containing an expansive material. The axisymmetric cylinder will be assumed to be frictionless. If the cylinder is not frictionless, some estimate of the friction characteristics may have to be obtained and used in the finite element computations. If the cylinder is not frictionless, the vertical expansion will produce vertical stresses in the cylinder walls (reduces hoop strain, ϵ_h) and there will also be arching radial force components which will increase the radial stress (increases hoop strain, ϵ_h). At this time the definition of cylinder restraint will be obtained by considering the pipe walls frictionless.

42. The problem is axisymmetric and is as presented in Figure 10.

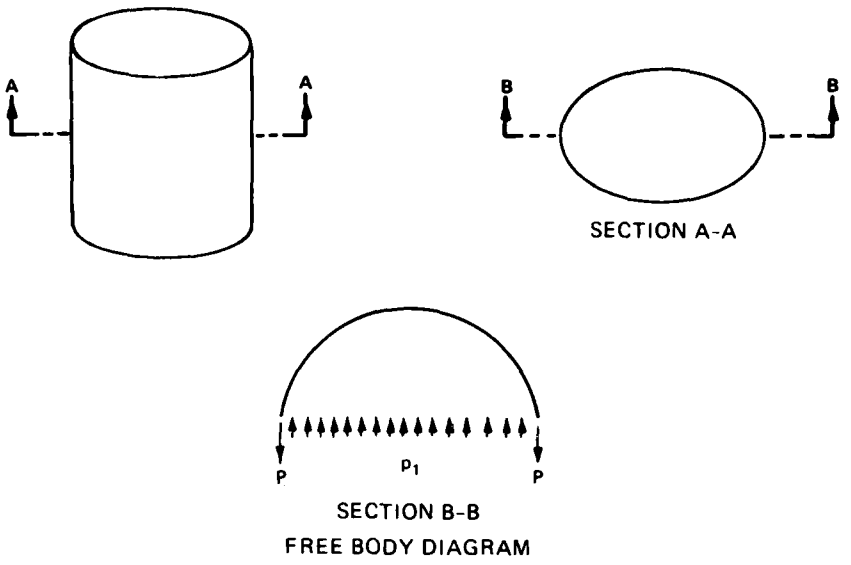


Figure 10. Pressurized cylinder and sections

43. The restraint in the cylinder walls will be defined as

$$R_c = \frac{\sigma_G}{\varepsilon_{h_c}} \tag{27}$$

to be consistent with the definition of the restraint of the expansion bar, where

σ_G = stress in expansive material at plug-pipe interface

ε_{h_c} = hoop strain at plug-pipe interface

A cross section perpendicular to the longitudinal axis of the cylinder and through its midpoint is shown in Figure 10.

44. A vertically cut section across the diameter of Section A-A is shown in Section B-B.

p_1 = pressure in pipe

D = diameter of pipe

r_1 = inside radius of pipe

From Section B-B a summation of forces in the direction of P yields

$$p_1 D \text{ (unit length)} = 2P \text{ (unit length)}$$

or

$$p_1 = \frac{P}{r_1} = \sigma_G \tag{28}$$

Substitute Equation 28 into Equation 27

$$R_c = \frac{p_1}{\epsilon_{h_c}} \tag{29}$$

R_c is the restraint of a frictionless steel cylinder.

45. From Figure 10, Section B-B, the circumferential strain is in the direction of p_c in the cylinder wall. This definition is consistent with the definition of restraint for the grout bar.

46. The consistent definition for the field environment is obtained from the equation of radial deflection of a thick-wall cylinder. The derivation of the deflection (Δ_1) is presented in Part II and is given in Equation 23. A free body of a thick-wall cylinder is taken, forces are summed, elastic equations are applied, and constants are evaluated to obtain Δ_1.

$$\Delta_1 = \frac{r_1 p_1}{E}\left(\frac{r_2^2 + r_1^2}{r_2^2 - r_1^2} + \mu\right)$$

Now take the limits Δ_1 as $r_2 \to \infty$.

$$\Delta_1 = \lim_{r_2 \to \infty} \frac{r_1 p_1}{E}\left[\frac{\frac{r_2^2}{r_2^2} + \frac{r_1^2}{r_2^2}}{\frac{r_2^2}{r_2^2} - \frac{r_1^2}{r_2^2}} + \mu\right]$$

$$= \frac{r_1 p_1}{E_f} + \frac{r_1 p_1}{E_f}\mu_f \tag{30}$$

47. This gives the radial deflection of the field environment in terms of the radius (r_1) of the borehole and the pressure (p_1) against the borehole for an infinite extent of host material. Rearranging Equation 30, we obtain

$$\frac{p_1 r_1}{\Delta_1} = \frac{E_{\text{field material}}}{1 + \mu_{\text{field material}}}$$

The restraint in the field environment is then

$$R_f = E_f = \left(1 + \mu_f\right)\frac{p_1}{\varepsilon_t} \tag{31}$$

This definition neglects free-field stresses which may already be present in the rock environment and act as confining stresses. The effect of confining stresses which are in the rock environment will be considered in the detailed analysis by an iterative solution which is generally discussed in Part V.

48. The only good correlation between the pressure created by the grout and the cylinder restraint is presented in Figures 11, 12, and 13. Considering Figure 11, if $R = \infty$, then $1/R = 0$; this corresponds to a full-restraint condition. In Figures 11 and 13, the full-restraint values can be obtained by extrapolating back to $1/R$ or $\varepsilon_r = 0$, respectively. This makes sense because for a specific expansive grout there should be a finite pressure for full restraint.

49. For less restraint ($1/R$ increasing) or more strain, the pressure should decrease and tend toward some specific values in Figures 11 and 13. The relations indicate that is what happens, but more data are needed to

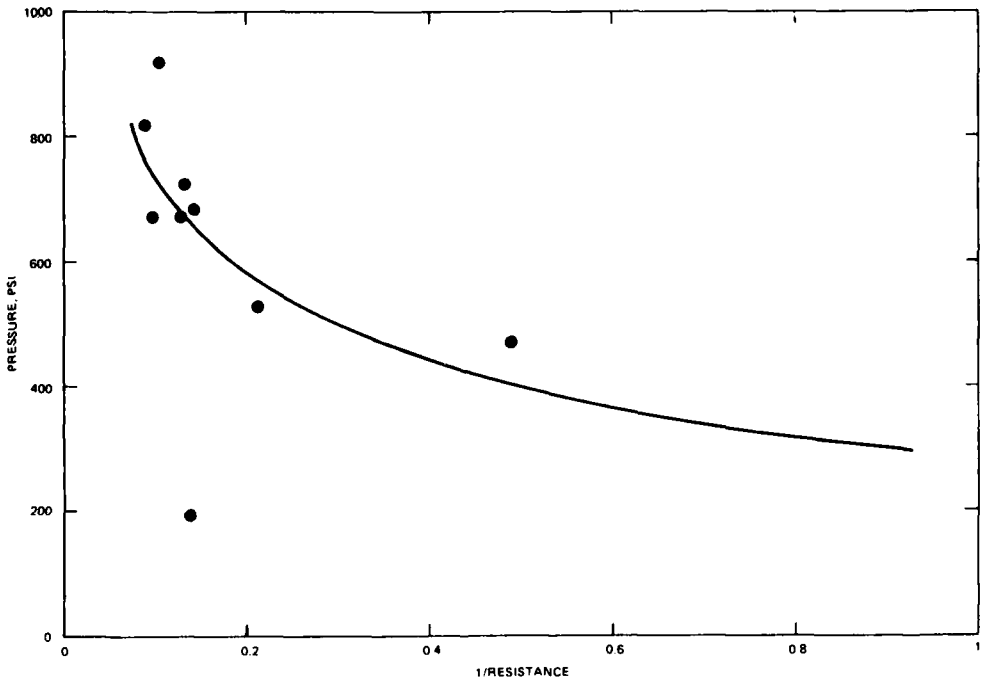


Figure 11. Pressure versus 1/restraint

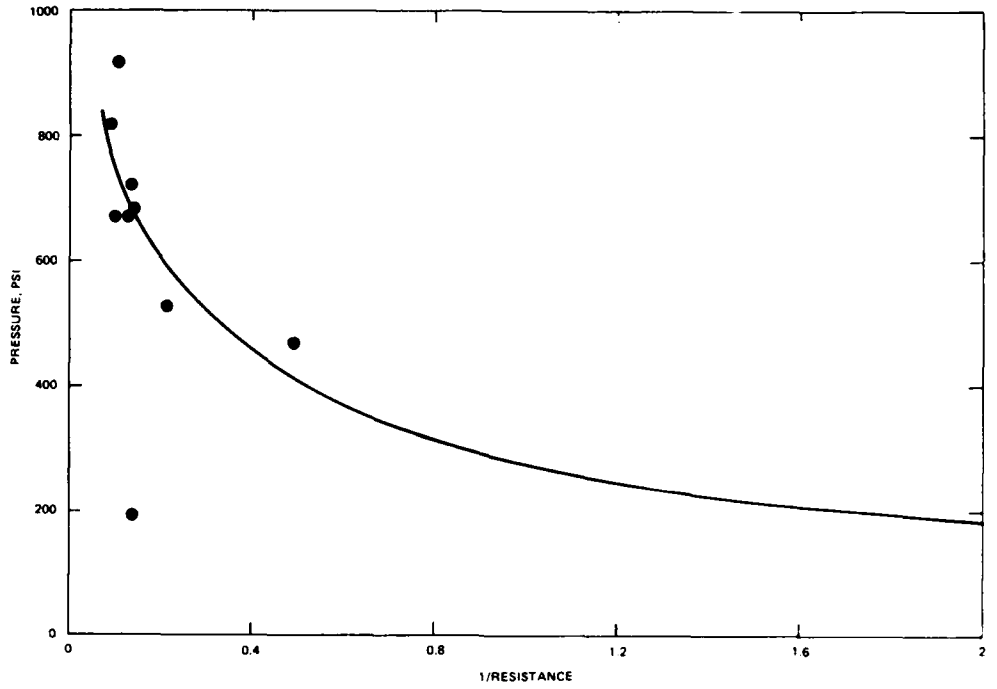


Figure 12. Scaled-up plot of Figure 11 pressure versus 1/restraint

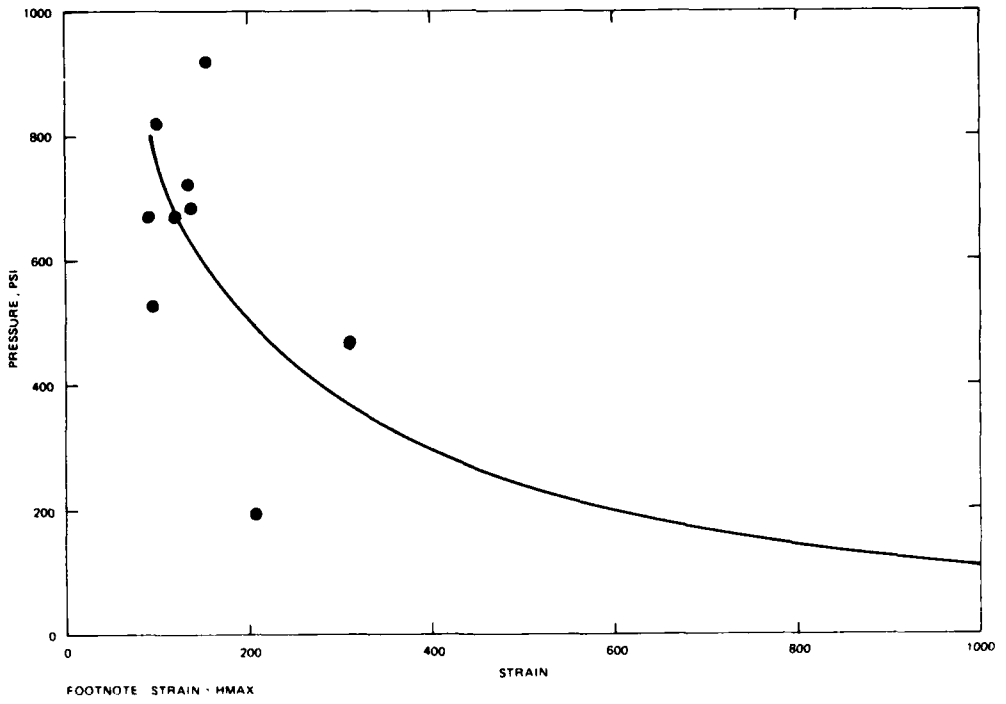


Figure 13. Pressure versus strain

define the specific shape of the curve. One way to approximate the curve shape is to take the unrestrained bar data and extend the relationship to the strain of the unrestrained bars.

Conclusions

50. Steel cylinders with various degrees of restraint can be used to determine expansive material properties. The definitions of restraint were made consistent for the expansive material tests in any steel cylinders, expansive grout bar tests, and a field environment without initial free-field stresses.

51. The calibrations for the test cylinders do not go through zero, which is probably a function of locked in stresses or nonuniform longitudinal strains created in the cylinder walls. Even though the calibrations do not go through zero and it seems that at $p = 0$ the ε should be zero, the calibration is correct for specific cylinders. The calibration is correct because the same pipe and gages are used for the calibration and the expansive grout test.

52. The fact that the calibration curves do not go through zero will shift the preliminary pressure-versus-time curves off of zero. That is, there is some pressure shown at zero time on the pressure-time curves.

53. The interaction of the steel cylinder and the expanding plug can be affected by an increase in temperature, by moisture conditions, or by the expansive characteristics of the expanding plug. The heat of hydration of cement in the grout causes the cylinder to expand initially and it is possible that at some point in time, there will not be any contact between the grout and the cylinder. Initially, the volume of the grout plug could remain constant or shrink with no indication in the strain gages because there must be pressure against the cylinder walls to activate the gages.

54. Temperature does not appear to have affected the first nine cylinder tests, but it did affect the pressure exerted by the grout in the tenth cylinder test. The effect of temperature on expansion may be due to the variation in time dependency between strength gain of the grout and expansion of the grout. The phasing of the strength gain with the development of expansion is important in optimizing expansion, as has long been known.*

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* American Concrete Institute. 1970. "Expansive Cement Concrete, Present State of Knowledge," Journal, American Concrete Institute, Vol 67, No. 8, pp 583-610.

55. The maximum strain (Figure 14) or pressure was considerably decreased, presumably because of the high temperature, in cylinder 10. This can readily be seen by using the value of $\epsilon_h = 75$. The corrected strain value is

$$\epsilon_h = 75 + 75 \left[(1.16 - 1)\ (1 - 1)\right] = 75 \frac{\mu in.}{in.}$$

$$\rho = (2.6)\ (75) + 17 = 212 \text{ psi}$$

$$\frac{1}{R_c} = \frac{1}{\frac{\rho_r}{\epsilon_h}} = \frac{1}{\frac{212}{75}} - = 0.35$$

From Figure 12, the values of $\rho = 212$ at $1/R = 0.35$ do not fit the graphical relationship.

56. The general trend of the correlation plots is probably correct even if there were drifts in the baseline voltages of the measuring system.

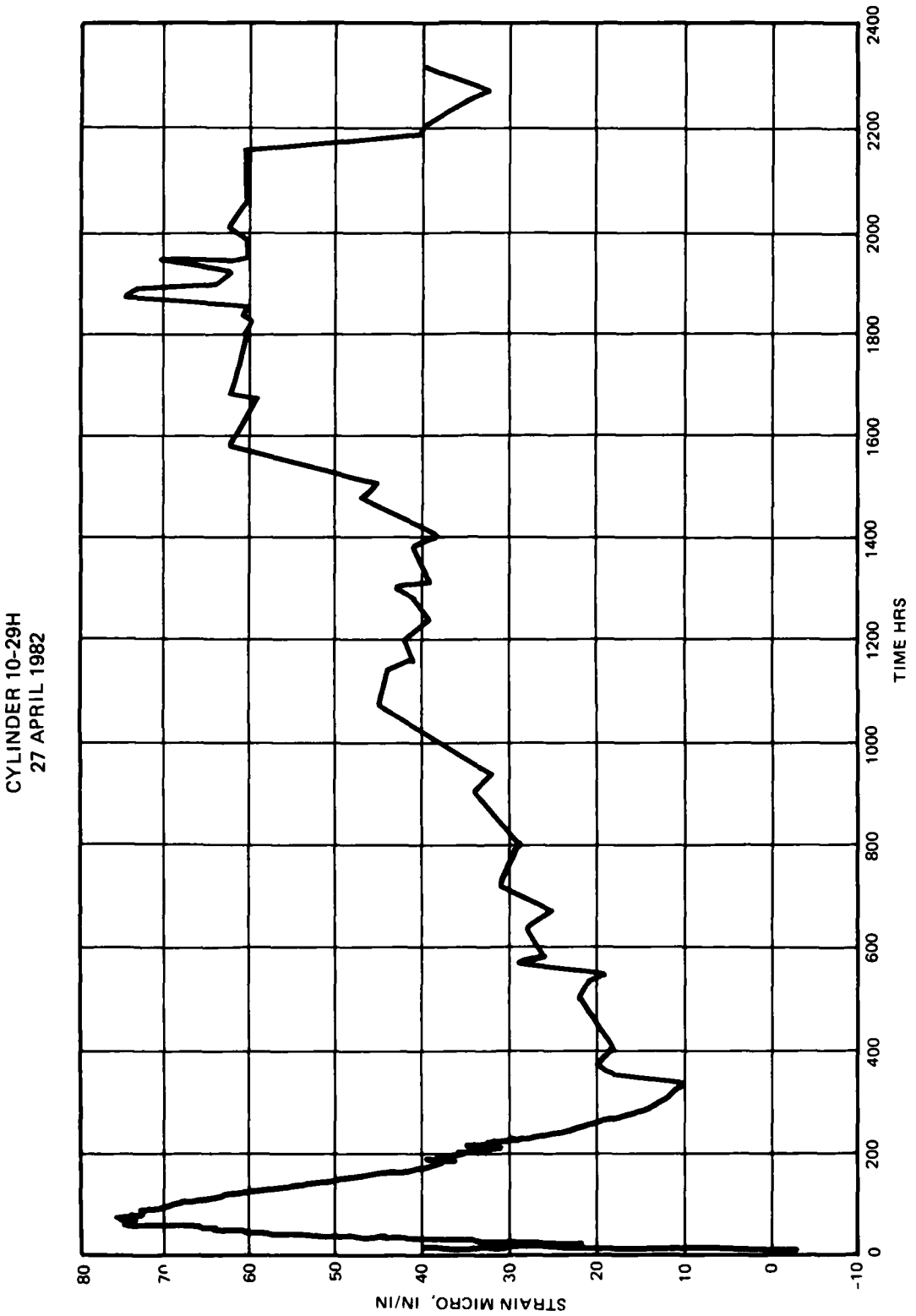

Figure 14. Strain versus time, cylinder 10

PART III: EXPANSIVE GROUT BAR AND VOLUMETRIC TESTS

Introduction

57. For many years, expansion characteristics of grout have been measured by molding restrained and unrestrained grout bars and accurately measuring their change in length.* Some indication of volume change is also obtained from bar specimens that are sealed from gain or loss of moisture and weighed in air and then in water at various time intervals to obtain their change in density. More accurate volume change can be obtained by filling balloons or impermeable flexible containers with the grout and obtaining their change in density with time.

Experimental Tests

58. For this study, the various types of bars which were cast and monitored are presented in Table 5.

59. The test method used was CRD-C 225-76 (ASTM C 806-75).** However, 3- by 3- by 10-in. restrained and 1- by 1- by 10-in. unrestrained bars were cast and monitored in addition to the 2- by 2- by 10-in. specimens required by the standard method.

60. The data that were obtained in this study for the BCT-1-FF grout mixture are presented in Figures 15-19. There were two unrestrained 1- by 1- by 10-in. specimens (Figure 15 and Table 6), two unrestrained 2- by 2- by 10-in. specimens (Figure 16 and Table 7), two restrained 2- by 2- by 10-in. specimens (Figure 17 and Table 8), and two unrestrained (Figure 18) and three restrained 3- by 3- by 10-in. specimens (Figure 19).

61. The method of relating the bar test data with the strains and pressures produced by the expansive grout contained in steel pipes of various restraints is illustrated. This relation will allow a prediction of pressure versus restraint in cylindrical cavities from bar test data. Before this is done, the relation between linear and volumetric expansion will be formulated.

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* Edward H. Rubin. 1973. "A Testing Agency's Experience with Expansive Cements," American Concrete Institute Special Publication No. 38, pp 341-351.

** American Society for Testing and Materials. 1983. ASTM Annual Book of Standards, Philadelphia, Pa.

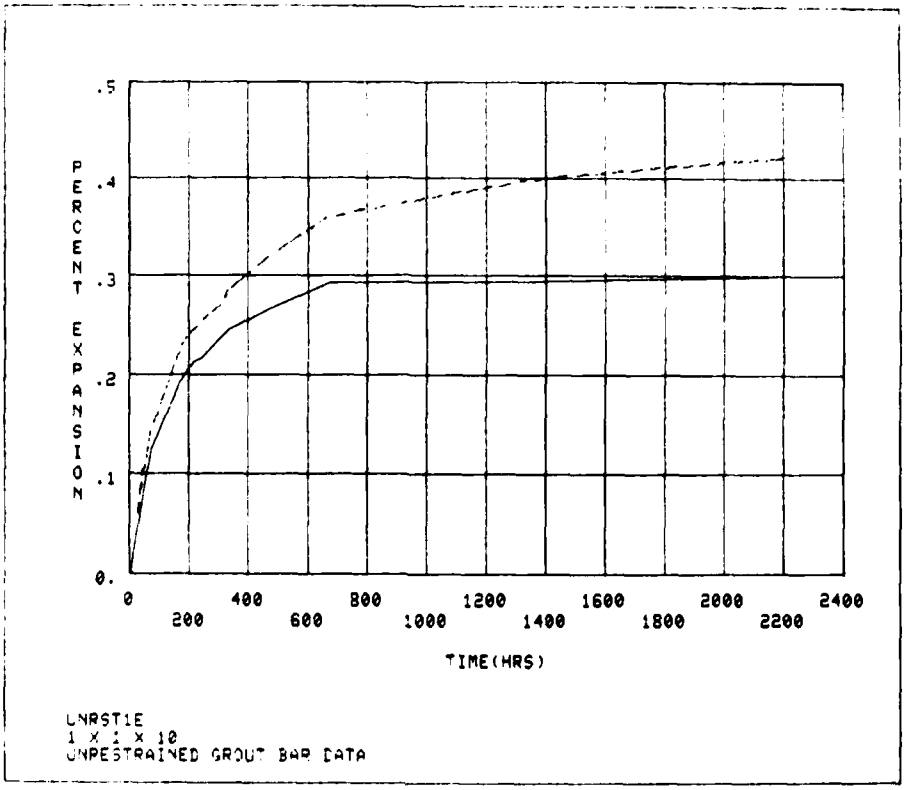

Figure 15. Percent expansion versus time, unrestrained 1- by 1- by 10-in. specimen

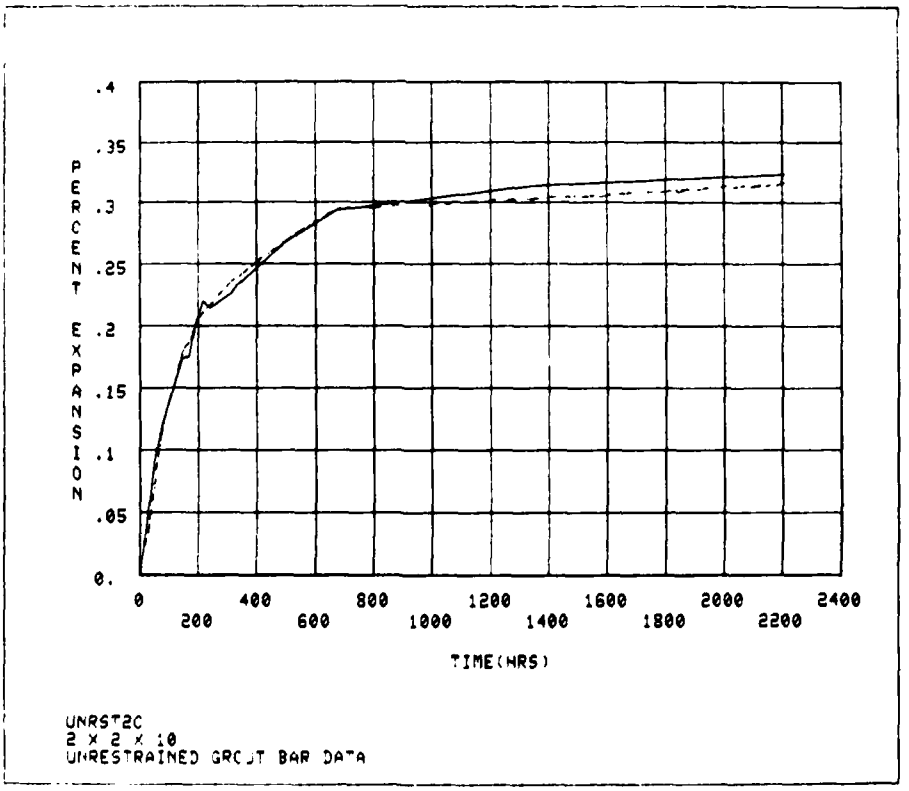

Figure 16. Percent expansion versus time, unrestrained 2- by 2- by 10-in. specimen

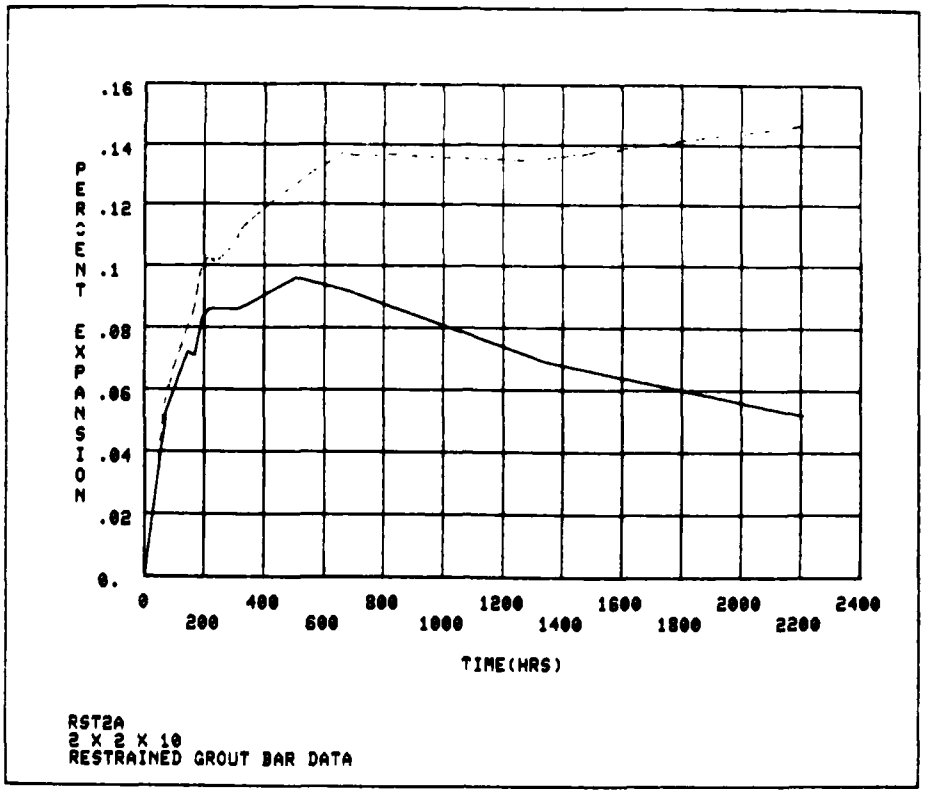

Figure 17. Percent expansion versus time, restrained 2- by 2- by 10-in. specimen

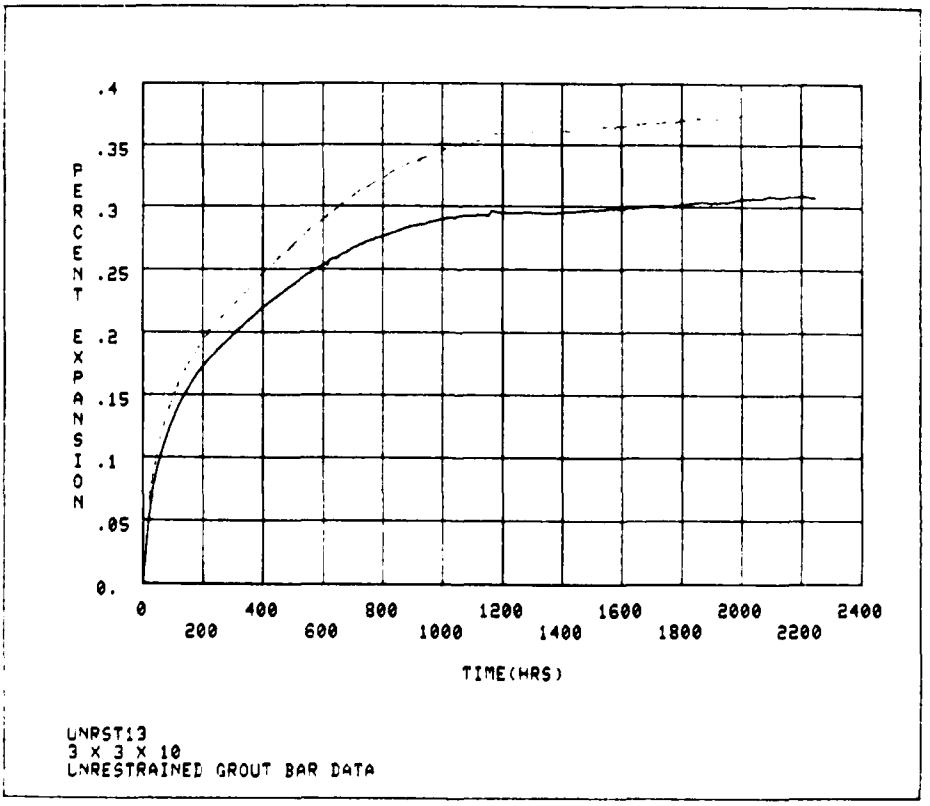

Figure 18. Percent expansion versus time, unrestrained 3- by 3- by 10-in. specimen

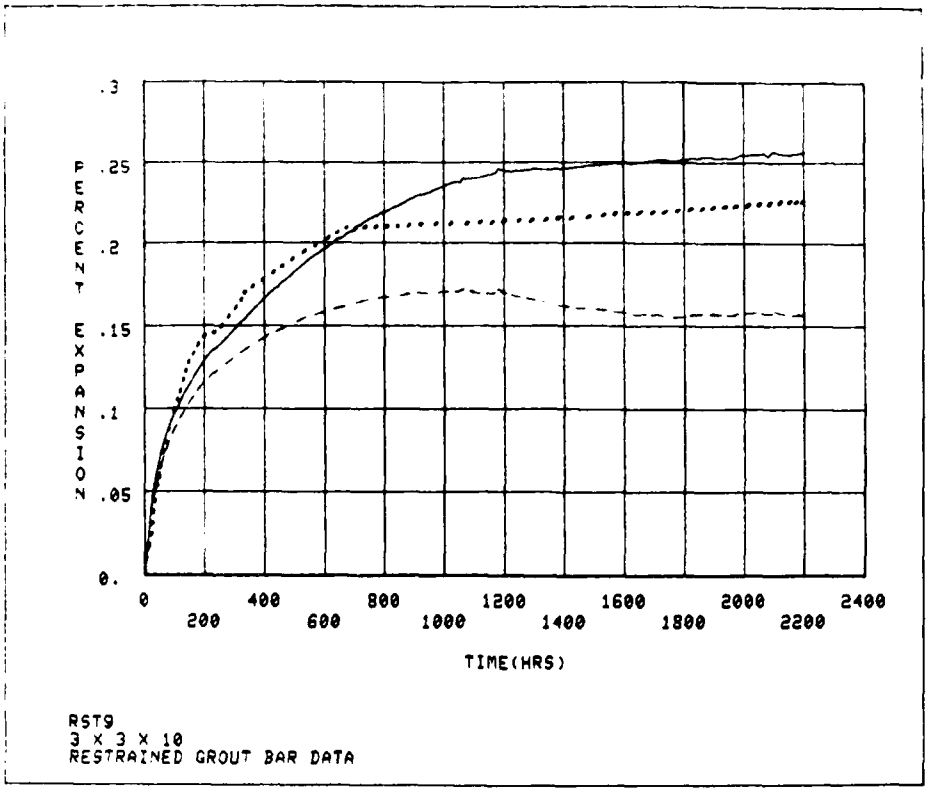

Figure 19. Percent expansion versus time, restrained 3- by 3- by 10-in. specimen

Linear Expansion Related to Volumetric Expansion

62. The expansion of the unrestrained grout is proportional to the length of grout in the direction in which the expansion is considered. Consider the grout bar in Figure 20.

ΔL is proportional to L

ΔW is proportional to W

also

$$\frac{\Delta W}{W} = \frac{\Delta L}{L} = \text{linear expansion} = \alpha$$

Initial volume = $(W)(W)(L)$

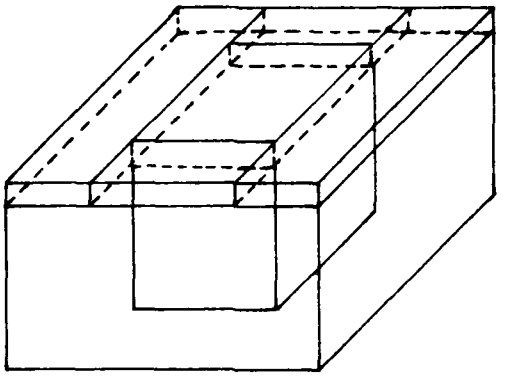

Figure 20. Expansion of a grout bar

$$\begin{aligned}\text{Final volume} &= (W + \Delta W)(W + \Delta W)(L + \Delta L)\\ &= (W^2 + 2W\Delta W + \Delta W^2)(L + \Delta L)\\ &= W^2L + 2W\Delta WL + \Delta W^2L + W^2\Delta L + 2W\Delta W\Delta L + \Delta W^2\Delta L\\ &= W^2L + 2W\Delta WL + W^2\Delta L + L(\Delta W)^2 + 2W\Delta W\Delta L + \Delta W^2\Delta L\end{aligned}$$

Neglect the second order and third order Δ terms. (They may or may not be negligible; this will be considered later.)

$$\text{Final volume} = W^2L + 2W\Delta WL + W^2\Delta L$$

Substitute $\Delta L = \alpha L$

$\Delta W = \alpha W$

$$\begin{aligned}\text{Final volume} &= W^2L + 2WL(\alpha)(W) + W^2\alpha L\\ &= W^2L + 2\alpha W^2L + \alpha W^2L\end{aligned}$$

$$\text{Volumetric expansion} = \frac{\text{Volume}_{\text{final}} - \text{Volume}_{\text{initially}}}{\text{Volume}_{\text{initially}}}$$

$$= \frac{W^2L + 2\alpha W^2L + \alpha W^2L - W^2L}{W^2L} \qquad (32)$$

$$= \frac{3\alpha W^2L}{W^2L} = 3\alpha$$

The volumetric expansion is equal to three times the linear expansion if the second and third order terms are neglected.

63. The second and third order terms are the Δ volumes along the edges of the bar as depicted in Figure 20 by the indicated outlines. This can easily be seen by computing the increase in volume neglecting the Δ volumes.

$$\text{Volume}_{\text{final}} - \text{Volume}_{\text{initially}} = (2)\left(\frac{\Delta L}{2}\right)(W)(W) + 4\left(\frac{\Delta W}{2}\right)(L)(W)$$

$$= \Delta L W^2 + 2\Delta W L W$$

Substituting $\Delta L = \alpha L$

$\Delta L = \alpha W$

$$\text{Volume}_{\text{final}} - \text{Volume}_{\text{initially}} = \alpha W^2 L + 2\alpha W^2 L$$

$$= 3\alpha W^2 L$$

64. This is the same answer as that obtained in Equation 32 when the second and third order terms were neglected.

65. This relation is probably only true for unrestrained expansion and for specimens with the same restraint and the same linear expansion in all directions.

66. The question of whether it is sufficiently accurate to neglect the second and third order terms in the equation for the expanded volume was examined. For a 10-in. bar, the error is about 1.97 percent for 2-percent linear expansion and 9.4 percent for 10-percent linear expansion. The important thing is to know that the volumetric expansion is only approximately equal to three times the linear expansion.

67. The approximation in most cases should not be used because the exact value which is a function of linear expansion can be determined.

68. By making volumetric computations and drawing conclusions from these computations, the following conclusions were obtained.

a. The volumetric expansion is a function of linear expansion. It is not a function of initial volume or shape. For example, it is 33.1 percent for 10-percent linear expansion and 6.12 percent for 2-percent linear expansion. The relation between volumetric expansion and linear expansion is unique and can be defined (Figure 21).

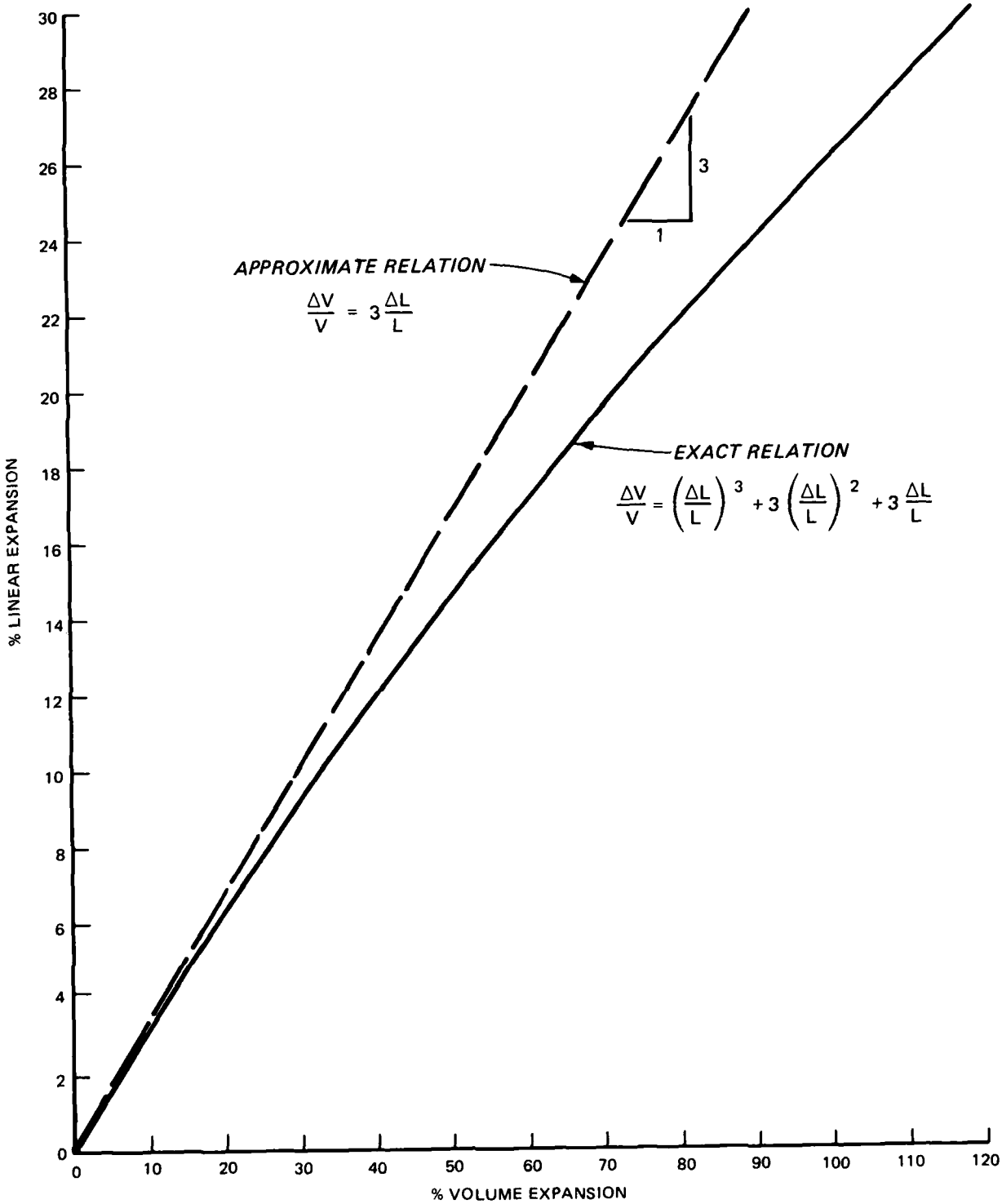

Figure 21. Percent linear expansion versus percent volumetric expansion

b. Since the percent volume change is constant for a constant percent linear expansion, the surface area is not an indicator of volume change. For example, with a constant percent linear expansion a volume can be molded to have many surface areas which would correspond to the same percent volume change.

The ratio of % volume expansion/% linear expansion is a variable. This variable can be calculated as follows for a cube:

$$\% \text{ Linear expansion} = \frac{\text{Final length} - \text{Original length}}{\text{Original length}}$$

$$= \frac{L + \Delta L - L}{L}$$

$$= \frac{\Delta L}{L}$$

$$\% \text{ Volumetric expansion} = \frac{\text{Final volume} - \text{Original volume}}{\text{Original volume}}$$

$$= \frac{(L + \Delta L)(L + \Delta L)(L + \Delta L) - L^3}{L^3}$$

$$= \frac{L^3 + 3L^2\Delta L + 3L\Delta L^2 + \Delta L^3 - L^3}{L^3}$$

$$= \frac{3L^2\Delta L + 3L\Delta L^2 + \Delta L^3}{L^3}$$

$$\frac{\% \text{ Volumetric expansion}}{\% \text{ Linear expansion}} = \frac{\dfrac{3L^2\Delta L + 3L\Delta L^2 + \Delta L^3}{L^3}}{\dfrac{\Delta L}{L}}$$

$$= 3 + \frac{3\Delta L}{L} + \frac{\Delta L^2}{L^2}$$

69. If the percent linear expansion is represented by α , the percent volumetric expansion can be expressed as percent volumetric expansion = $3\alpha + 3\alpha^2 + \alpha^3$. This relation between linear and volumetric expansion is true for all shapes. The extension of the relation from a cube to any shape can be visualized by considering any shape as being made up of many small cubes. The relation is true for each tiny cube as has been shown above; therefore, it is true for the sum of the cubes which equals the actual volume of expansive material. For someone who becomes concerned about the total volume of the shape being represented by cubes it is clear that as the number of cubes increase we get closer and closer to sweeping out any volume under consideration and for an infinite number of cubes the total volume is considered. In our extended visualization the number of cubes will approach infinity.

Linear Expansion of Unrestrained Grout Bars Versus Expansion of Restrained Grout Bars

70. The unrestrained and restrained expansion of bars are related as follows and as shown in Figure 22.

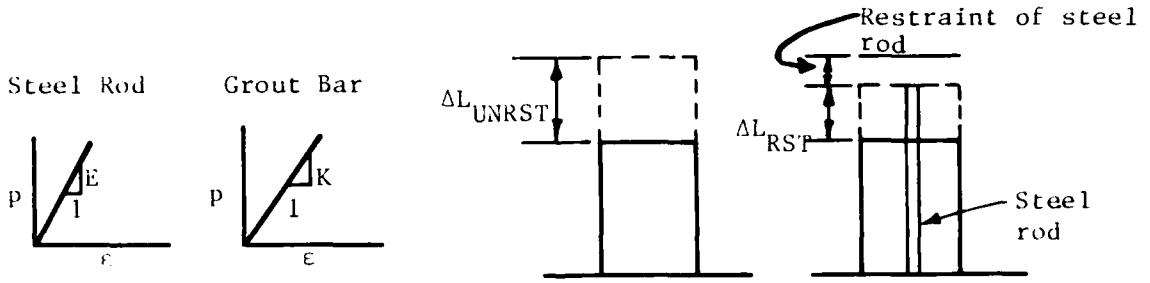

Figure 22. Unrestrained and restrained bar expansion

Relate $\Delta L_{UNRST}/\Delta L_{RST}$ for a given size grout bar.

Force in steel rod = fully restrained grout force - force relieved due to grout expansion in the restrained bar

$$A_{Rod}\ E_{Rod}\ \frac{\Delta L_{RST}}{L} = K\left(\frac{\Delta L_{UNRST}}{L}\right) A_{Grout} - K\left(\frac{\Delta L_{RST}}{L}\right) A_{Grout}$$

$$\frac{\Delta L_{UNRST}}{\Delta L_{RST}} = \frac{A_{Rod}\ E_{Rod} + KA_{Grout}}{KA_{Grout}}$$

$$= 1 + \frac{A_{Rod}\ E_{Rod}}{KA_{Grout}}$$

71. If the pressure-strain relation (K) is not linear for the grout, the above equation will be modified by a summation of incremental expansive effects over the length of expansion.

72. The area and modulus of elasticity of the steel rod as well as the pressure restraint properties of the grout are very important in this relationship.

73. The K in the above equation is

$$K = \frac{F}{\Delta L} = \frac{(p_1 - p_2)A}{(\epsilon_2 - \epsilon_1)L}$$

From the restraint curve for the grout (considering pressure versus strain as a measure of restraint)

$p = f(\epsilon)$

the slope is $-\frac{\Delta p}{\Delta \epsilon}$. Then $K = \frac{df(p)}{d\epsilon}\ \frac{A}{L}$.

Tests of 1- by 1- by 10-in. Unrestrained Bars

74. The linear expansion data are presented in Table 6 and are plotted in Figure 15. From Figure 15 it can be seen that there is a great deal of variation between the linear expansion of the two test specimens. The variation exists even though the grout was mixed very uniformly in a one-batch mix. The plot of the linear expansion data for each specimen shows a good trend which indicates it is good data but there is a variation between the two bars. The average linear expansion is given in Table 6. The relation between

the volumetric and linear expansion should be approximately 3 as has been indicated in the previous analysis, but as can be seen in Table 6 the relation starts at less than 1 and increases to greater than 3. The ratio may vary due to a variability of moisture in the grout and sealing material and there could be some change in volume of the material which is used to seal the water into the grout specimen. At this time, the volumetric expansion data from the bars are considered to be too inaccurate for practical use.

75. The general trend of expansion data from the bars does not agree with the grout expansion as indicated by the pipe tests (this could be due to a drift in baseline voltage for the pipe measurements). The bars indicated continual expansion for as long as they were monitored (2,208 hr).

76. The data for the 1- by 1- by 10-in. unrestrained grout bars were first compared with the pipe data. The 14-day expansion of the grout bars was compared with the maximum expansion for the pipe data. The unrestrained bar with an expansion or strain near the time of maximum expansion for the pipes should give a p value of zero. This will tell where the relation of p versus ε_h or p versus $1/R$ should intersect $p = 0$.

77. The average linear expansion (strain) at 14 days for the 1- by 1- by 10-in. unrestrained grout bars is 0.265 percent linear expansion or 2,650 μin./in. strain. This means the curve in Figure 13 should be zero at 2,650 μin./in. strain. This seems reasonable from Figure 13.

Tests of 2- by 2- by 10-in. Bars

Unrestrained tests

78. The percent linear expansion and volumetric data for the unrestrained and restrained 2- by 2- by 10-in. specimens are presented in Tables 7 and 8, respectively.

79. The average strain for the unrestrained 2-in. specimens at 14 days is 2,360 μin./in., which is fairly close to that of the 1-in. bars, which is 2,650 μin./in. The strain for each of these bars should be the same; therefore, an average of these values is approximately 2,500 μin./in. This value seems reasonable when considering that the pressure should be zero in Figure 15 for a strain of approximately 2,500 μin./in.

Restrained tests

80. The restraint will be considered to see if the pressure-restraint

correlation for the bar data agrees with the pressure-restraint correlation for the pipe data. Load-strain curves for rods similar to those used in the experimental tests were obtained. From the given deflection of a grout bar with a similar restraining rod, the force in the steel rod can be obtained.

81. Next, the pressure exerted by the 2- by 2-in. square grout bar is calculated. From the test data for the steel rods, the forces produced by each of the two grout bars at 870 μin./in. and 1,130 μin./in. strain are, respectively, 620 and 800 lb. The pressure is then

$$p_1 = \frac{620 \text{ lb}}{2 \text{ in.} \times 2 \text{ in.}} = 155 \text{ psi}$$

$$p_2 = \frac{800 \text{ lb}}{2 \text{ in.} \times 2 \text{ in.}} = 222 \text{ psi}$$

$$\text{Average} \approx 178 \text{ psi}$$

82. The relations of p versus 1/R (Figure 11) and p versus ε_h (Figure 13) will not only be valid for tests of expansive grout in steel cylinders, they will be valid for any restraining environment. Definitions of terms are as follows.

p = pressure exerted by the cylindrical grout specimen (psi)

R = restraint of restraining environment $\frac{(\text{psi})}{\text{in./in.}}$

ε_h = hoop strain at the interface of the expanding grout and the restraining environment (in./in.)

The steel containers are simply vehicles to restrain the expansive grout material. After the relationship between pressure exerted by the expanding grout and the restraint or strain at the interface of the grout and restraining environment has been obtained, the relation is good for any environment of a known restraint.

83. The restraint (using average values of forces and strain for the 2- by 2-in. grout bar) of the grout bar is

$$R_B = \frac{\sigma_B}{\varepsilon_B} = \frac{710}{(1{,}000)_4} = 0.18 \frac{\text{lb}}{\text{in./in.}}$$

or

$$\frac{1}{R_B} = \frac{1}{0.18} = 5.6 \frac{\text{in./in.}}{\text{lb}}$$

From Figure 12, using $1/R_B = 5.6$ (in./in.)/lb, $P_B = 178$ psi is a reasonable pressure.

Tests of 3- by 3- by 10-in. Bars

Unrestrained tests

84. There were two unrestrained 3- by 3-in. specimens. Each specimen was monitored automatically by the use of linear variable differential transformer (LVDT) gages and readout equipment. The data for these two specimens are presented in Figure 18.

85. The average percent linear expansion at 24 days is 0.2127 or 2,127 μin./in. strain. This is fairly close to 2,650 μin./in. and 2,360 μin./in. strain for the unrestrained 1- by 1-in. and 2- by 2-in. specimens, respectively.

Restrained tests

86. There were three restrained 3- by 3-in. specimens. One specimen was monitored manually (specimen 4) and the other two were monitored automatically by the use of LVDT gages and readout equipment. Data for the three specimens are presented in Figure 19.

87. The restraining rods in the 3- by 3-in. specimens were smaller than those in the 2- by 2-in. specimens, and the modulus of elasticity for the rods in the 3- by 3-in. specimens varied. Therefore, it is best to calculate the individual forces exerted by the specimens and then obtain an average of the forces exerted.

Specimen	E, psi	Strain at 14 Days μin./in.	Load from Load Strain Curves lb force
4	30.9×10^6	1,710	510
7	28.1×10^6	1,504	540
8	29.7×10^6	1,332	510
			Average 520

88. The average force exerted by the 3- by 3-in. specimens was 520 lb. This corresponds to

$$p = \frac{520}{3 \text{ in.} \times 3 \text{ in.}} = 58 \text{ psi}$$

89. The average restraint of the grout bar is

$$R_{B_{3 \text{ in.} \times 3 \text{ in.}}} = \frac{520}{(1{,}515)(9)} = 0.038 \frac{\text{lb}}{\text{in./in.}}$$

$$\frac{1}{R_{B_{3 \text{ in.} \times 3 \text{ in.}}}} = \frac{1}{0.038} \approx 26 \frac{\text{in./in.}}{\text{lb}}$$

From Figure 12, $p = 58$ psi could be a reasonable pressure value.

Volumetric Data from Balloon Tests

90. Expansive grout was poured into two balloons and their volume change was determined automatically by knowing their original weight in air and continuously monitoring their weight while submerged in water. Their corrected volume change is presented in Figures 23 and 24.

91. It is apparent from Figures 23 and 24 that the percent volume gain varies significantly between specimens. The specimen represented by Figure 23 shows over three times the percent volume change of that represented in Figure 24.

92. Figures 23 and 24 show approximately 8-percent and 25-percent volumetric expansion at 2,208 hr or 92 days age. From Tables 6 and 7 and Figure 19, the average percent linear expansions are 0.36, 0.32, and 0.35, respectively, at 92 days. Three times these values are 1.08, 0.96, and 1.05, respectively. The volumetric data show much more expansion than is indicated by the bar data. It was found that the balloons used for these tests did let water penetrate and collect between the balloon and the grout. This caused the above discrepancy. The expansion indicated by the bar data is the most reliable. Better sealing material will have to be used in future tests for volumetric expansion.

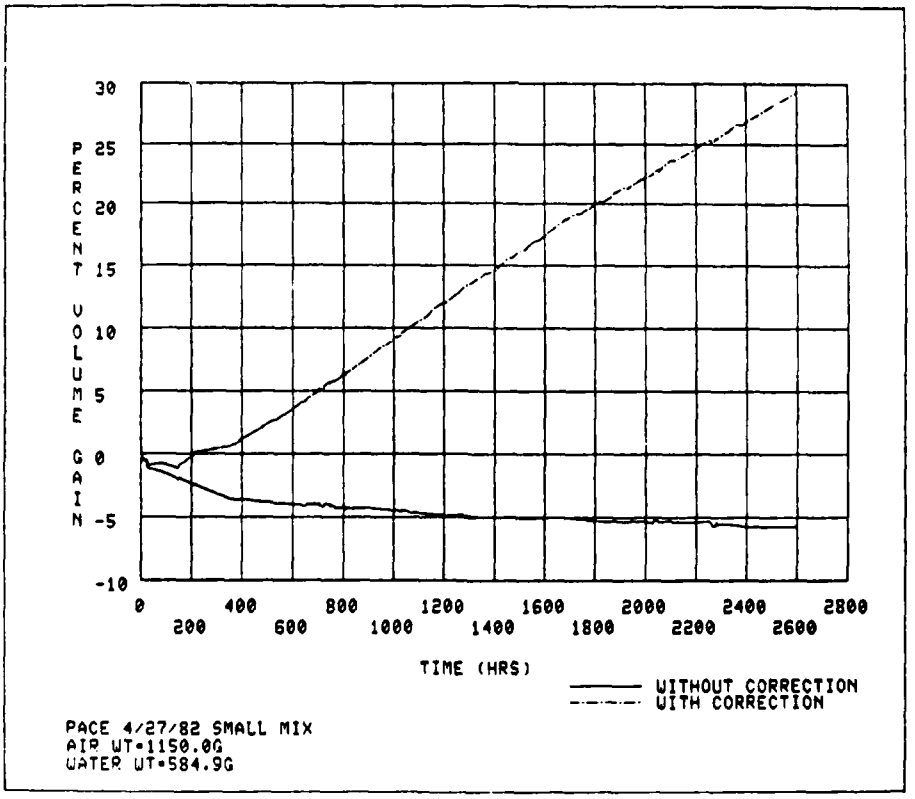

Figure 23. Percent volume given versus time, specimen 1

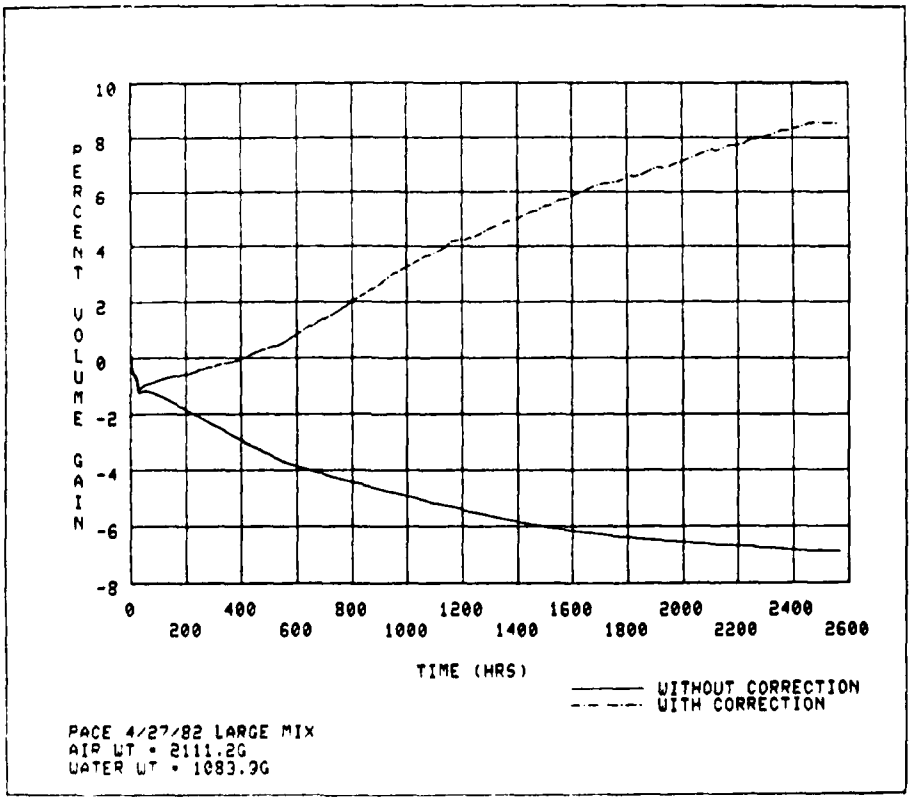

Figure 24. Percent volume gain versus time, specimen 2

PART IV: OPTIMUM TEMPERATURE FOR MAXIMUM EARLY EXPANSION OF CONCRETE

93. A test that has been used as an indicator of the expansiveness of a grout is performed by pouring the expansive grout into glass jars. If the grout breaks the jar, this is taken as an indication that the grout has expanded. The time at which the jars break in a given temperature environment quickly gives a rough idea of the similarity of the grout to expansive grout previously cast in similar jars.

94. This test can also be used to give an indication of how fast the grout exerts expansive pressure in environments of varying temperatures. The grout will produce a pressure on the inside of the jar before the jar breaks, and after the jar breaks, the test is complete; therefore, this test does not determine the amount of expansion or pressure created in the different temperature environments. While this test only gives indications about early expansion, it can still be used as an indicator of the expansiveness of the grout in various temperature environments. This is especially true for temperatures below 110° F.

95. The main finding from the jar tests is that there is a characteristic temperature at which maximum early expansion of a grout occurs. Jars were filled with expansive grout and were placed in various temperature environments. The jars were observed regularly and it was noted when they broke. The time of break was taken halfway between the last time the jar was observed unbroken and the time it was observed broken. The data in the various temperature environments were averaged and are plotted in Figure 25. It can be seen that early expansion is obtained between approximately 85° and 110° F. If the maximum expansion corresponds to the earliest expansion, then this would also be the optimum temperature for maximum expansion. For temperatures between 85° and 110° F, the early expansion probably corresponds very closely to the maximum expansion.

96. The jar tests have shown the dependency of expansion on temperature and the fact that there is an optimum temperature for maximum expansion.

97. Several other observations resulted from the jar test. It was noted, for instance, that there is a lower and an upper temperature at which the expansion is not significant. At 130° and 0° F the jars did not break.

98. Some jars in approximately a 77° F temperature environment were

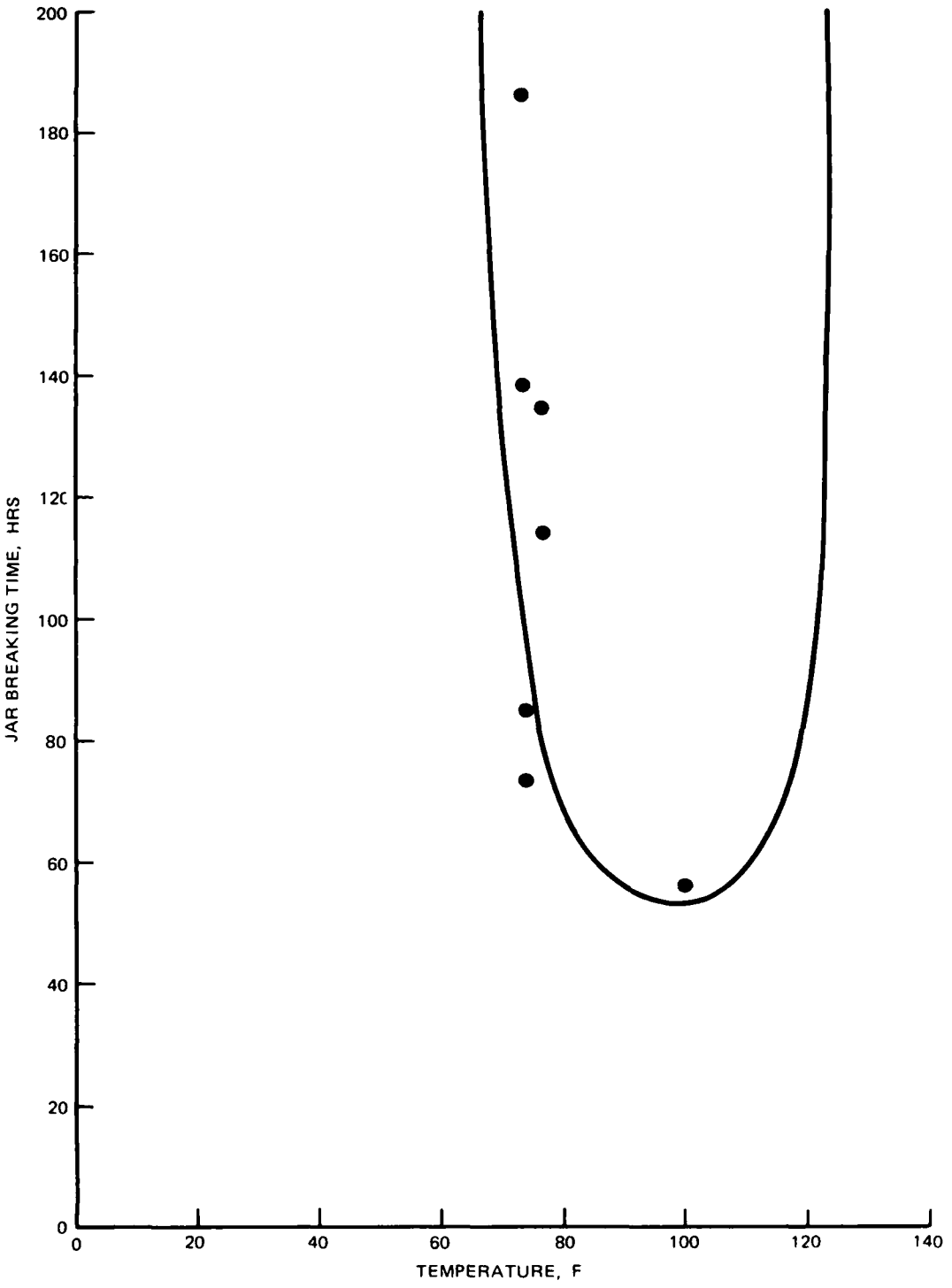

Figure 25. Jar breaking time versus temperature

partially filled with grout and they broke in the same time span as those jars that were full. This confirms that the expansion occurred mainly after the grout had become a solid and that insignificant expansion relief was present due to expansion in the vertical direction.

99. The opposite was true in the 0° F environment. Even though the jars never broke, there was expansion of the grout in the vertical direction such as to bend the jar lid upward. It expanded before it was set such that it had significant vertical expansion.

100. Expansion depends on the relationship of the phasing of strength gain and expansive product formation.

101. The temperature curve for expansion of a given mixture should be defined. This should be done such that the optimum range of temperature for early expansion is known. The optimum temperature curve for compressive strength and maximum expansion should also be determined.

PART V: FINITE-ELEMENT SOLUTION OF BOREHOLE PLUGGING PROBLEMS

102. The pressure-versus-restraint relations can be used in an iterative solution to obtain the maximum and minimum principal stress and deformation fields in the plug and surrounding environments. The concept of equal deflection at the interface of the plug and host material is an important concept in the analytical solution of the borehole plugging problem. The iterative solution can be obtained as follows:

a. The pressure-versus-restraint and pressure-versus-strain relations will be known for the sealing plug (Figure 26).

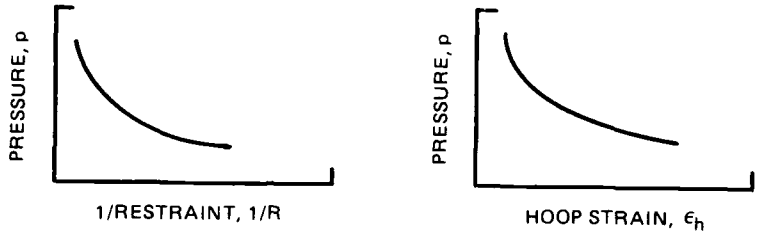

Figure 26. Illustrative example of pressure versus 1/restraint and pressure versus strain

b. An approximate restraint can be calculated for the field environment and can be used in the pressure versus 1/restraint relation to obtain an estimated pressure to initially apply against the borehole wall.

c. The estimated pressure will be exerted against the sides of the borehole and a finite-element analysis performed using the rock properties and boundary conditions. From the finite-element analysis, the interface element node point strains will be determined.

d. The strain associated with each interface node point for the problem being considered and for the originally assumed pressure will be determined from a figure such as p versus ϵ_h of Figure 26.

e. If the strain calculated from the finite-element analysis and that from Figure 26 do not agree (the deflection of host and plug at their interface is not equal), a new pressure for each interface element is calculated using numerical analysis techniques.

f. The finite-element analysis will then be rerun with the new pressures and the above calculations and comparisons made.

g. This iterative process will continue until the finite-element calculated strains and the strains from Figure 26 agree within some reasonable limit (less than some specified value).

h. The solution will be obtained when the finite-element calculated strains and the strains from Figure 26 agree within some reasonable limit.

i. The final interface pressures can be applied by a finite-element analysis to the plugging material to determine the stresses in the plug.

103. Numerical analysis procedures which are already programmed will be used in a subroutine separate from the finite-element analysis to obtain fast convergence of the iterative solution. Probably only two to four finite-element runs will be necessary for convergence.

104. The axisymmetric finite-element analysis is inexpensive. The solution of a problem without iteration (Figure 27 presents the grid) costs only $14.73.

105. The finite-element analysis can be used for the solution of the borehole plugging problem for any shape of plug and for any rock environment. The solution will be more time-consuming and expensive if the geometry and material properties are not axisymmetric.

106. It is almost impossible to obtain the values of stress concentration in a layered environment or at the ends of the grout plug by closed-form computations. The finite-element analysis can be used to obtain these stresses, which can be quite high.

107. The finite-element analysis is an incremental analysis and will allow solutions for shear and normal stresses along the interface of the grout plug and the cavity material. Shear stresses can be estimated from the shear strains which are produced in the pipe tests. This will allow the determination of the most effective length of grout plug for a given environment. The length of grout plug can be too long and cause excessive shear stresses on the face of the cavity walls.

108. In the above solution, test conditions with respect to temperature and moisture must fit the actual field environment which is being considered.

109. An alternate way to solve the interaction between the expanding grout plug and the host rock is to define the expansion of the plugging material by various parameters and then use these parameters, along with the properties of the host material, to determine a solution by the finite-element analysis. The procedure described in paragraph 102 above is simpler and does not require a knowledge of the parameters affecting the expansion process; therefore, this procedure was selected.

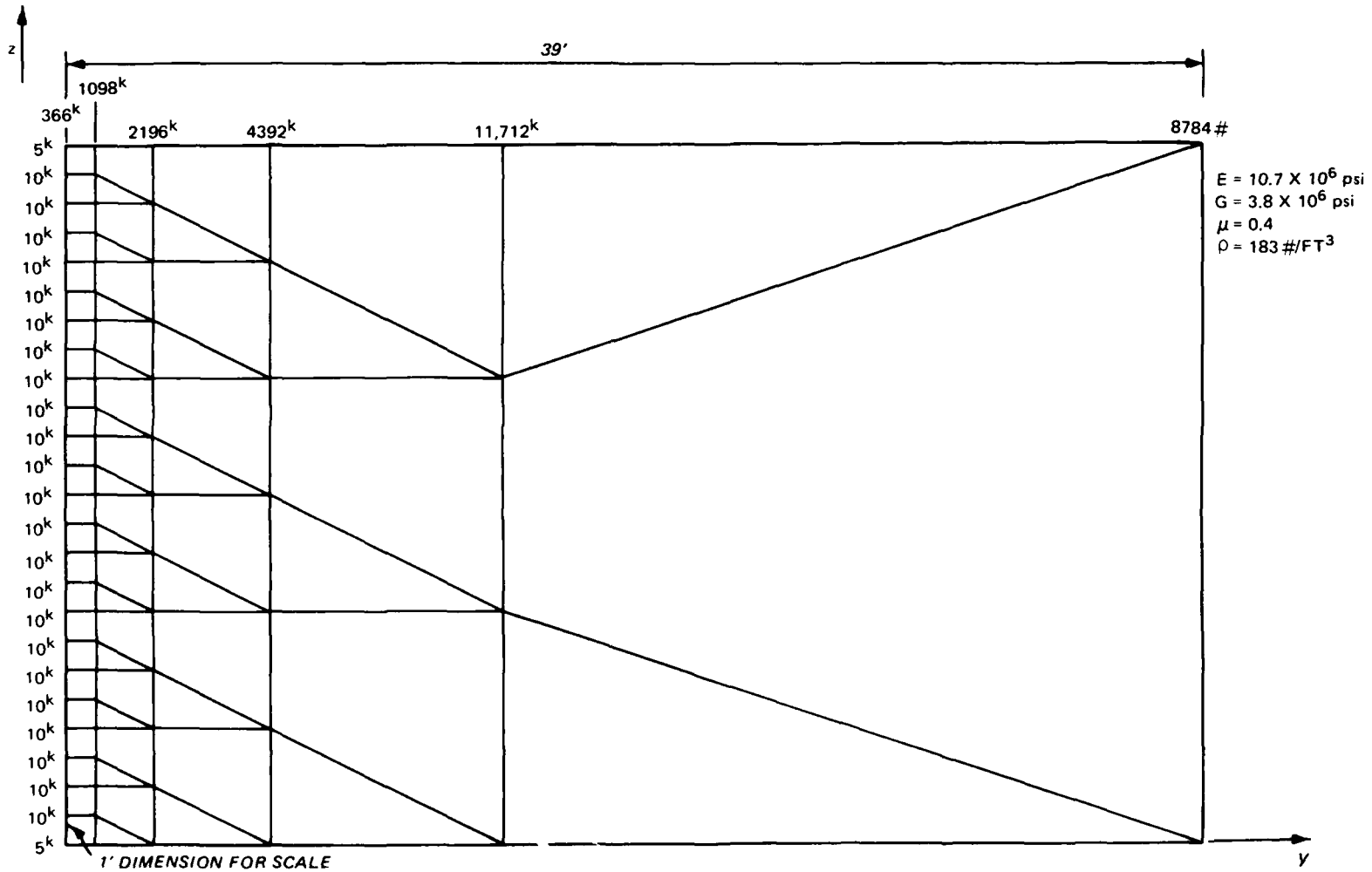

Figure 27. Axisymmetric analysis, undeformed grid

PART VI: CONCLUSIONS AND RECOMMENDATIONS

110. It is important to develop the technology by which a rock cavity environment can be evaluated for safety in relation to being plugged and used as a storage container for hazardous waste materials. A structural evaluation can be made if the relevant properties of the host material and the pressure-versus-restraint relation of the plugging material are known.

111. The relevant properties of the material which forms the cavity can be obtained by conventional testing procedures. The pressure-versus-restraint relation of the plugging material can be obtained by using steel cylinders having different inside diameters, wall thicknesses, or both, and hence varying degrees of restraint. A pressure-versus-restraint relation for an expansive mixture can be determined as was illustrated in Figures 11, 12, and 13. These curves are for illustration purposes; the scatter in the data could be contributed to by shifts in baseline voltage of the data acquisition system. These pressure-versus-restraint relations can be used in a finite-element analysis to determine the stresses in a rock environment which is plugged with an expansive mixture if detrimental temperatures are not encountered. If the temperature is high enough to affect the pressure-versus-restraint relation, the effect must be known and the pressure-versus-restraint relation used for the specific situation under consideration.

112. The finite-element analysis can be used to obtain the stresses and deflections for any expansive grout plug in a restrained environment; then, by knowing the relevant properties of the material, the performance in the structural situation can be evaluated.

113. It is recommended that the range of expansion characteristics of plugging mixtures necessary for practical borehole plugging situations be determined. The optimum expansive mixture should then be determined for these environments.

114. It is recommended that a set of standard pipes be selected and the most promising borehole mixtures be tested to determine their expansion with time. The most promising of the mixtures could then be tested to see what its properties would be when subjected to various temperatures.

115. The expansive grout specimens in cylindrical steel containers can be subjected to varying moisture conditions and a range of responses

determined. The response appropriate to the field situation can be selected for analysis purposes.

116. It is recommended that pressure restraint curves similar to those in Figures 11, 12, and 13 be extended for the selected borehole plugging mixtures. This extension should at least be over the range of actual practical rock environments which may be encountered in a borehole plugging program.

117. It is recommended that appropriate computer programs be linked together with instructions for a finite-element solution which will iterate and obtain stress fields in any environment affected by an expanding grout seal.

118. It is recommended that a finite-element analysis be performed and an evaluation be made determining the safety of any potential hazardous waste storage.

119. A study of plug expansion and durability should be made in relation to the development of strength gain and expansion. If the mixture is too weak when expansion occurs, it will deform in the direction of the least resistance; if it is too strong, the mass will resist the expansion.

120. The cause or causes of extraordinary variations in the expansion of material from the same batch should be determined.

121. Stress in physical situations may affect properties such as permeability, compressive and tensile strengths, durability, etc., reflected by test results which are determined for unstressed specimens. It is suggested that tests be conducted to determine if realistic stress conditions affect short- and long-term properties which are used in evaluating the safety of borehole plugging situations.

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Table 1

Data for Laboratory and Field BCT-1-FF Grout Mixtures, Proportions (Weight, %)

	Laboratory	Field	
		9/26/79	2/14/80
API class H cement	52.2	53.1	52.7
Fly ash	17.6	18.1	18.2
Expansive additive	7.0	7.1	7.5
Dispersant (D65)	0.2	0.1	0.2
Defoamer (D47)	0.02	0.02	0.02
Water	23.0	21.6	21.4
Properties			
Water/cementitious material ratio	0.30	0.28	0.27
Fluid density, g/cm^3	1.98	2.11	2.11
Fluid density, lb/gal	16.5	17.6	17.6

Table 2

Physical Properties of Hollow Steel Cylinders

Cylinder	Gages	Physical Dimensions: Inside Radius, in. r_1	Physical Dimensions: Outside Radius, in. r_2	Physical Dimensions: Cylinder Length, in. L_1	Calibration Constants: $p = m_1\varepsilon_H + B_1$ m_1	Calibration Constants: $p = m_1\varepsilon_H + B_1$ B_1	Calibration Constants: $p = m_2\varepsilon_\ell + B_2$ m_2	Calibration Constants: $p = m_2\varepsilon_\ell + B_2$ B_2
1	11H	1.29	1.35	46.5	1.58	-4.48		
	10V						7.63	6.96
2	13H	0.76	0.90	30.0	6.18	24.62		
	12V						27.65	143.81
3	15H	1.65	1.85	35.5	4.35	-0.79		
	14V						18.19	-3.72
4	17H	1.18	1.45	36.0	9.48	39.73		
	16V						40.08	42.87
5	19H	1.25	1.45	38.0	6.21	22.72		
	18V						23.86	90.69
6	21H	1.25	1.45	24.5	5.63	11.47		
	20V						23.62	145.89
7	23H	1.25	1.45	24.5	6.01	23.21		
	22V						23.58	-10.80
8	25H	1.18	1.45	24.0	8.16	43.32		
	24V						35.80	84.53
9	27H	1.18	1.45	24.5	8.67	18.24		
	26V						37.48	209.49
10	29H	6.11	6.50	58.5	2.60	16.97		
	28V						8.06	14.43

Table 3

Data from Expansive Grout Tests in Steel Cylinders

Cylinder	Gages	Steel Cylinder Restraint (psi)/μin./in. R_c	Theoretical Calculations $\frac{\epsilon_{max_{hoop}} \text{ (open ends)}}{\epsilon_{max_{hoop}} \text{ (closed ends)}}$	Column 5 Measured Maximum Strains from Pipe Tests μin./in. ϵ_h	Column 5 Measured Maximum Strains from Pipe Tests μin./in. ϵ_ℓ	Calculated Pressures Using Calibration Equations and Column 5 Strains psi p_h	Calculated Pressures Using Calibration Equations and Column 5 Strains psi p_ℓ
1	11H	1.58	1.16	260.0		406	
	10V				105.0		808
2	13H	6.18	1.13	65.0		426	
	12V				30.0		973
3	15H	4.35	1.14	185.0		804	
	14V				46.0		833
4	17H	9.48	1.12	75.0		751	
	16V				24.0		1,005
5	19H	6.21	1.13	89.0		575	
	18V				41.0		1,069
6	21H	5.63	1.13	110.0		631	
	20V				34.0		949
7	23H	6.01	1.13	112.0		696	
	22V				29.0		673
8	25H	8.16	1.12	75.0		655	
	24V				67.0		2,483
9	27H	8.67	1.12	64.5		577	
	26V				26.0		1,184
10	29H	2.60	1.16	—		—	
	28V				—		—

Table 4

Strains and Pressures of BCT-1-FF Produced in Steel Pipes

Cylinder	Measured Maximum Strain μin./in. ε_h	Measured Maximum Strain μin./in. ε_ℓ	Calculated for Fluid Pressure Situation Based on Maximum Hoop Strains from Grout Tests μin./in. ε''_ℓ	Adjustments to Strains to Make Linear Calibration have $\varepsilon = 0$ at $p = 0$ μin./in. ε_h	Adjustments to Strains to Make Linear Calibration have $\varepsilon = 0$ at $p = 0$ μin./in. ε_ℓ	Adjusted Strains for Calibration to have $\varepsilon = 0$ when $p = 0$: Hoop μin./in. ε_h	Adjusted Strains for Calibration to have $\varepsilon = 0$ when $p = 0$: Longitudinal μin./in. ε_ℓ	Longitudinal Strain for Fluid Pressure as Related to Max ε_h, ε''_ℓ μin./in.	$\varepsilon_{\ell\,measured} / \varepsilon''_{\ell\,fluid\ pressure}$	ε_h Corrected to Equivalent Fluid Pressure Situation μin./in.	ε_h Corrected to Grout Interface μin./in.	Pressure for ε_h Corrected
1	260	105	52	-2.84	0.91	257	106	53	2.00	298	312	471
2	65	30	10	3.98	5.21	69	35	15	2.33	81	96	501
3	185	46	44	-0.18	-0.20	185	46	44	1.04	186	208	809
4	75	24	18	4.19	1.07	79	25	19	1.32	82	101	777
5	89	41	20	3.66	3.80	93	45	24	1.88	104	121	646
6	110	34	21	2.04	6.18	112	40	27	1.48	119	138	670
7	112	29	30	3.86	-0.46	116	28	29	0.97	116	135	697
8	75	67	16	5.31	2.36	80	69	18	3.83	107	155	873
9	64.5	26	10	2.10	5.59	67	32	16	2.00	75	92	650
10	75	0		6.53	1.79							

Table 5

Grout Bar Tests

Time at Which Data are Obtained from Grout Bars, days	Bars		
	1 by 1 by 10 in.	2 by 2 by 10 in.	3 by 3 by 10 in.
Initial	Unrestrained Data Only	Unrestrained and Restrained Data	Unrestrained and Restrained Data
2			
3			
4			
5			
6			
7			
8			
9		Restrained data are obtained by the use of a 1/4-in. threaded steel rod connected in the center of end plates. The grout is cast around the rod and between the end plates.	Restrained data are obtained by the use of a 3/16-in. threaded steel rod in the same manner as the 2- by 2- by 10-in. specimens.
10			
11			
12			
13			
14			
21			
28			
56			
92			

Table 6

Unrestrained 1- by 1- by 10-in. Expansive Grout Bar Data (Monitored Manually)

Age days	Specimen C			Specimen D			Average
	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	Percent Linear Expansion
Initial							
2	-0.3312	0.087	--	-0.0374	0.098	--	0.0925
3	-0.1325	0.125	--	0.0000	0.144	0.0000	0.1345
4							
5							
6	-0.1325	0.174	--	0.1869	0.202	0.9252	0.188
7	0.0000	0.192	0.0000	0.2991	0.224	1.3353	0.208
8	-0.0331	0.204	--	0.3364	0.237	1.4194	0.2205
9	0.0331	0.213	0.1554	0.3738	0.244	1.5320	0.2285
10	0.662	0.217	0.3051	0.4112	0.251	1.6382	0.2340
11							
12							
13	0.0331	0.239	0.1385	0.4112	0.270	1.5230	0.2545
14	0.0331	0.246	0.1346	0.4486	0.284	1.5796	0.2650
21	0.0662	0.271	0.2443	0.6355	0.324	1.9614	0.2975
28	0.0331	0.293	0.1130	0.7477	0.357	2.0943	0.3250
56	-0.1325	0.294	--	0.9346	0.394	2.3721	0.3440
92	-0.2319	0.300	--	1.4953	0.417	3.5859	0.3585

Table 7

Unrestrained 2- by 2- by 10-in. Expansive Grout Bar Data (Monitored Manually)

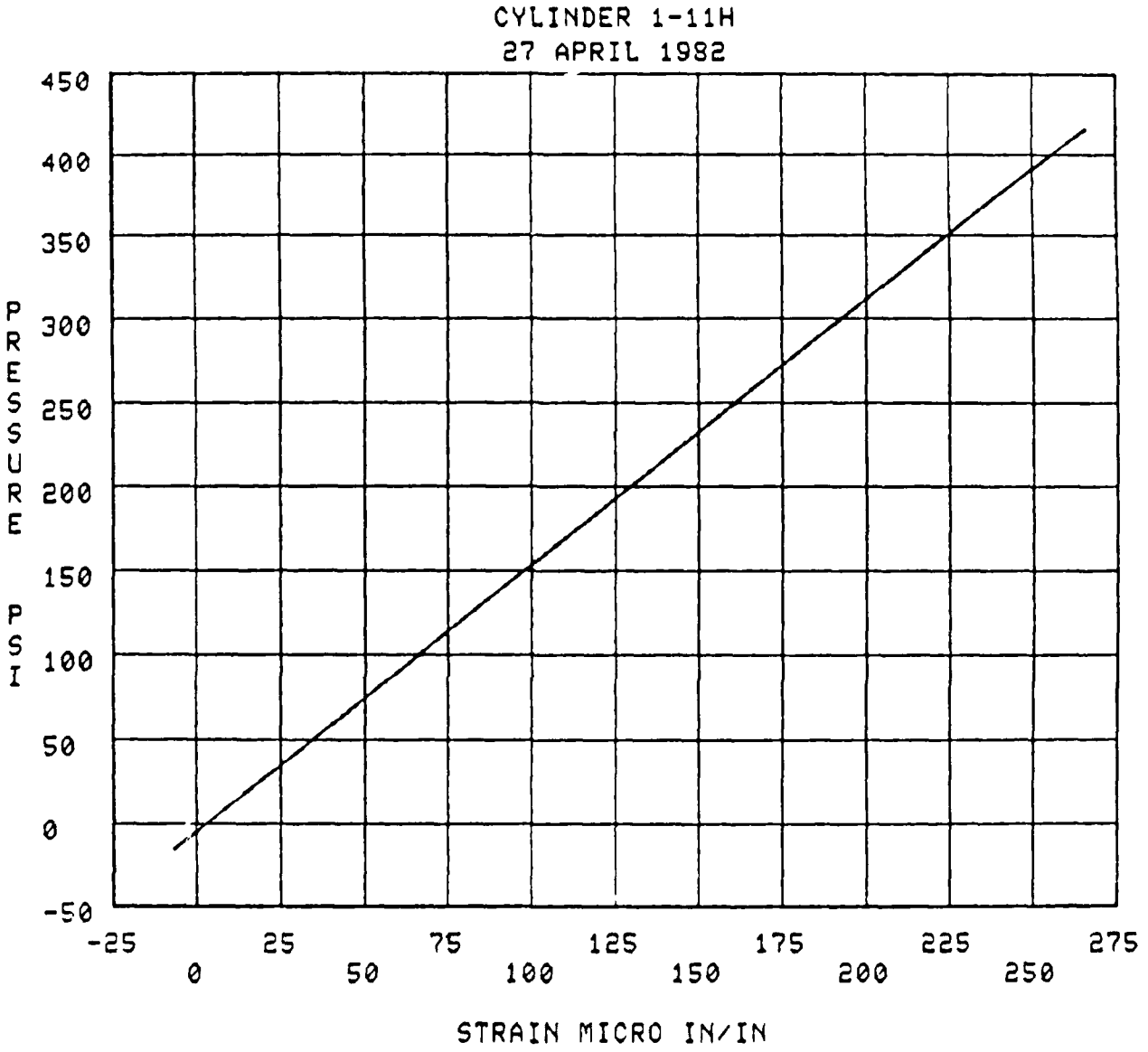
Age days	Specimen C			Specimen D			Average Percent Linear Expansion
	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	
Initial							
2	0.01535	0.090	0.1706	0.0324	0.077	0.4203	0.0835
3	0.3290	0.118	2.7881	0.1942	0.117	1.6598	0.1175
4							
5							
6	0.5045	0.173	2.9162	0.4962	0.179	2.7721	0.1760
7	0.6032	0.175	3.4469	0.6149	0.187	3.2882	0.1810
8	0.6471	0.203	3.1877	0.6688	0.205	3.2624	0.204
9	0.6800	0.219	3.1050	0.7228	0.211	3.4256	0.215
10	0.7787	0.214	3.6879	0.8522	0.216	3.9454	0.215
11							
12							
13	0.8335	0.225	3.7044	0.7983	0.236	3.3826	0.2305
14	0.8555	0.233	3.6717	0.8738	0.239	3.6561	0.2360
21	1.0858	0.268	4.0515	1.0032	0.269	3.7294	0.2685
28	1.1845	0.293	4.0426	1.1219	0.294	3.8159	0.2935
56	1.4367	0.313	4.5901	1.3700	0.302	4.5364	0.3075
92	1.7986	0.323	5.5684	1.7799	0.315	5.6506	0.3190

Table 8

Restrained 2- by 2- by 10-in. Expansive Grout Bar Data (Monitored Manually)

Age days	Specimen C			Specimen D			Average Percent Linear Expansion
	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	Percent Volume Expansion	Percent Linear Expansion	Ratio Volume to Linear Expansion	
Initial							
2	-0.2719	0.036		-0.0245	0.040		0.038
3	-0.1483	0.053		0.2574	0.059	4.3627	0.056
4							
5							
6	0.1236	0.072	1.7167	0.6500	0.080	8.1250	0.076
7	-0.0494	0.071		0.7113	0.086	8.2709	0.0785
8	0.0989	0.083	1.1916	0.7972	0.099	8.0525	0.0910
9	0.1360	0.086	1.5814	0.8462	0.103	8.2155	0.0945
10	0.1607	0.086	1.8686	0.8707	0.101	8.6208	0.0935
11							
12							
13	0.2101	0.086	2.4430	1.0056	0.107	9.3981	0.0965
14	0.1978	0.087	2.2736	1.0424	0.113	9.2248	0.100
21	0.3090	0.096	3.2188	1.2509	0.126	9.9278	0.1105
28	0.2595	0.092	2.8211	1.3736	0.137	10.0259	0.1145
56	0.1854	0.069	2.6870	1.5330	0.135	11.3556	0.102
92	0.2225	0.052	4.2781	2.2075	0.146	15.1199	0.099

APPENDIX A: TEST CYLINDER CALIBRATIONS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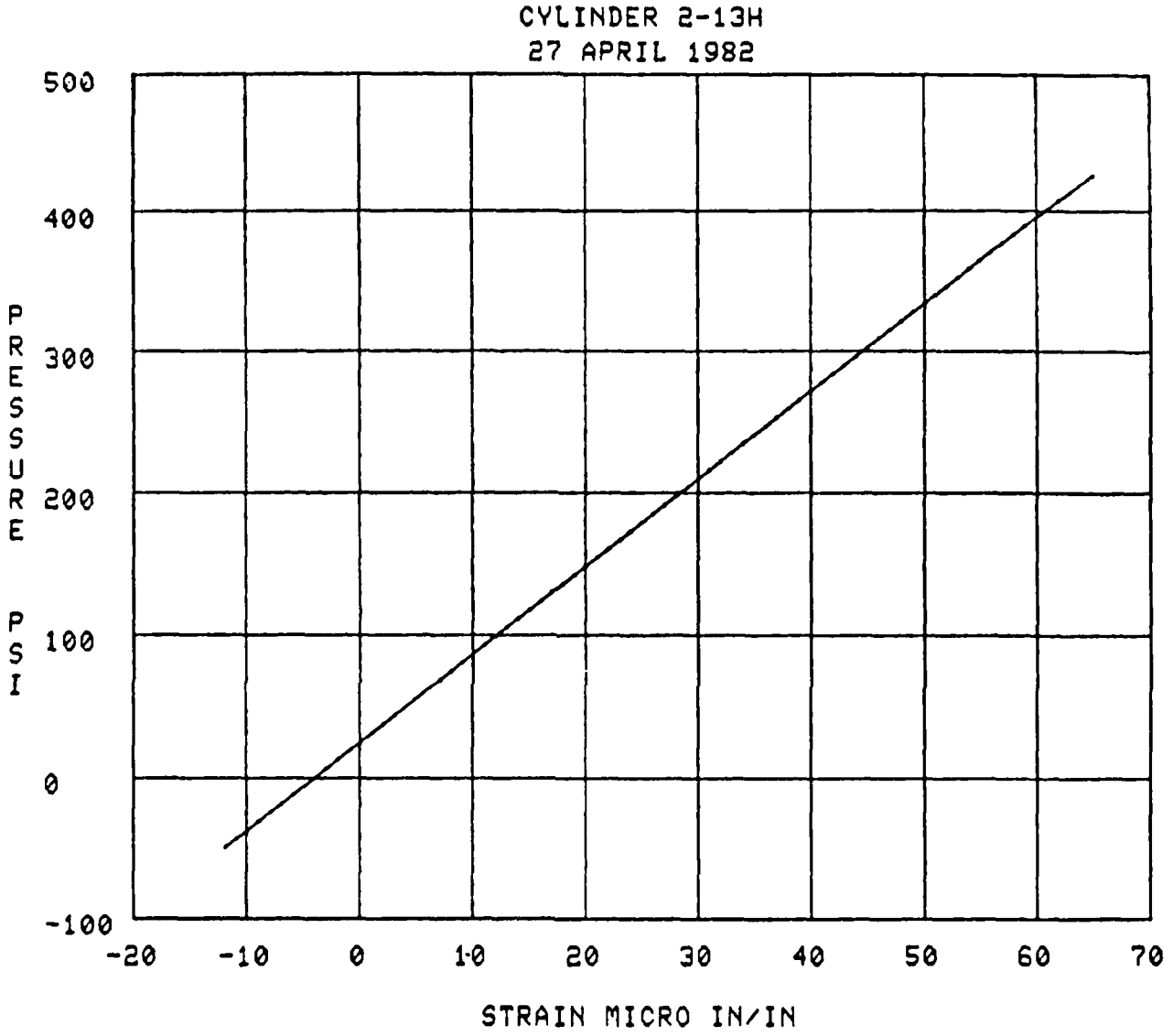
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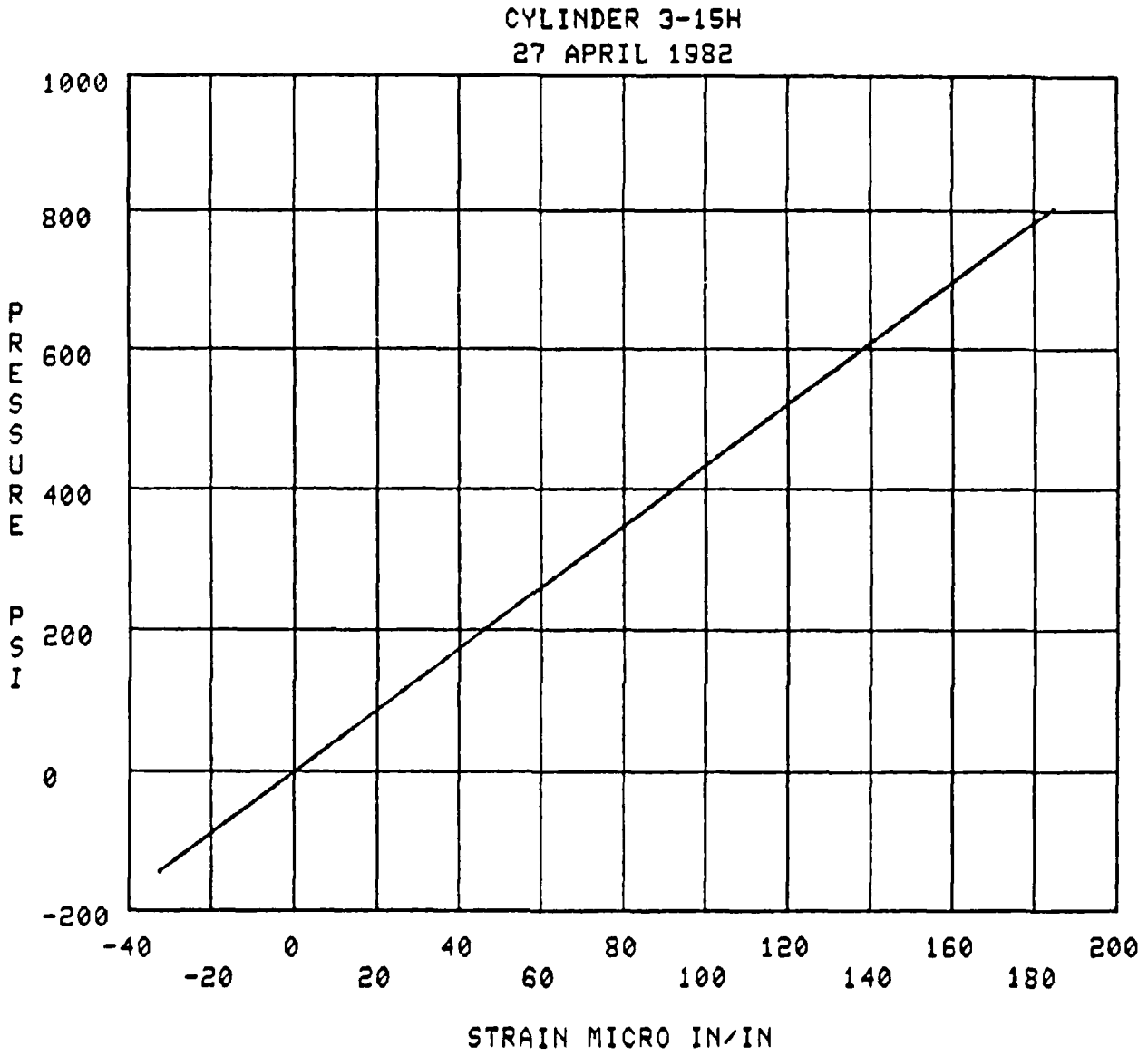
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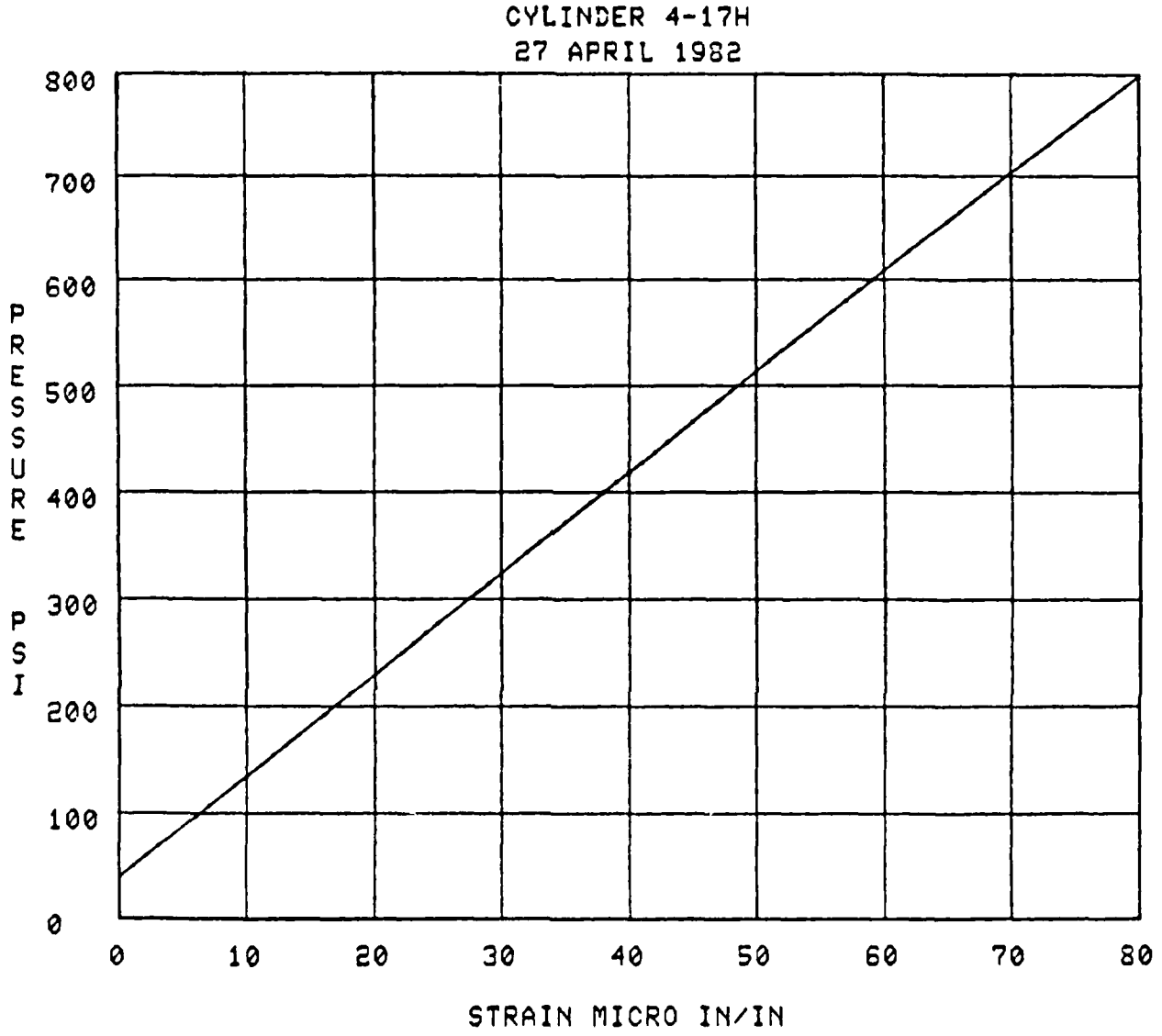
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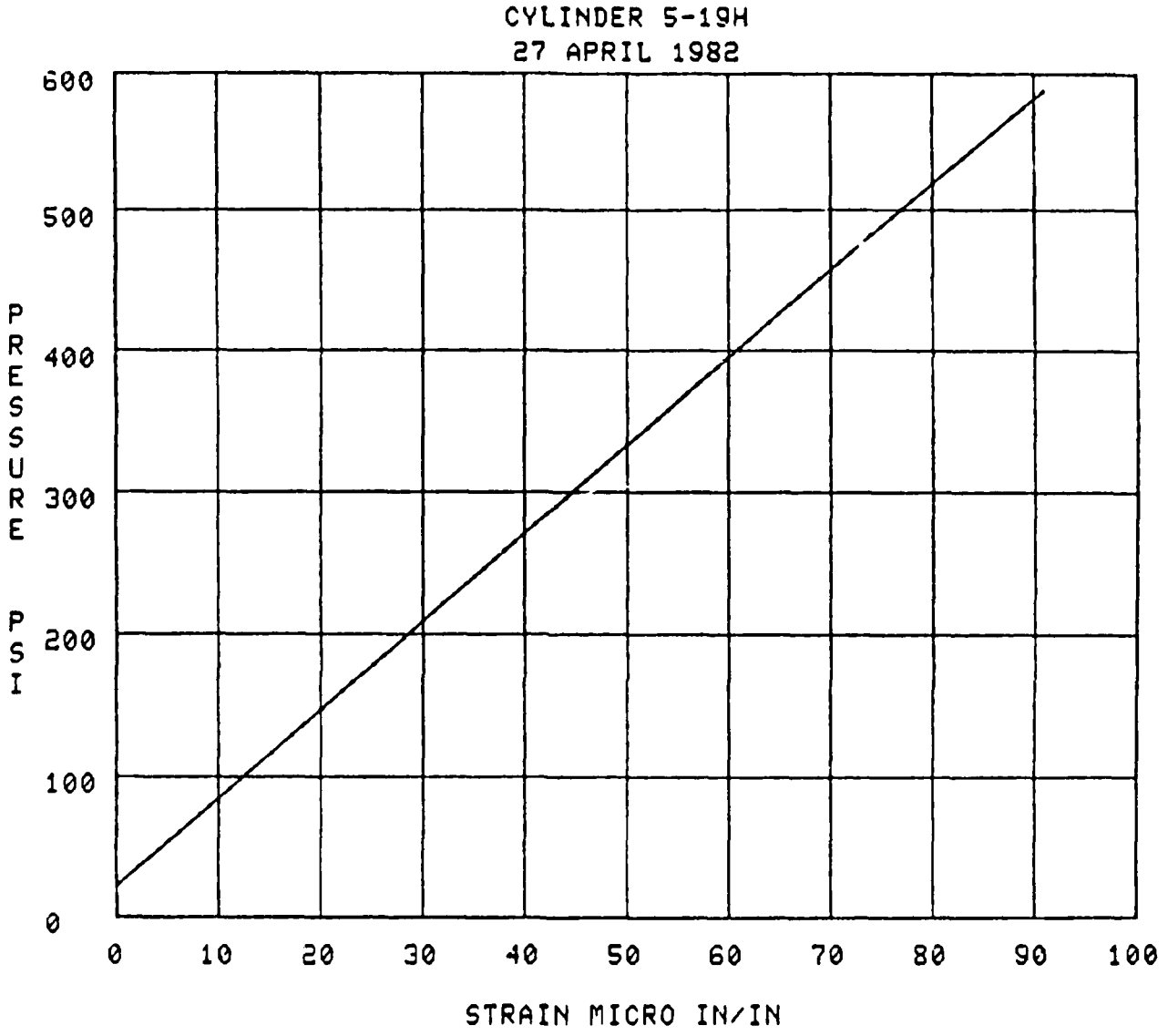
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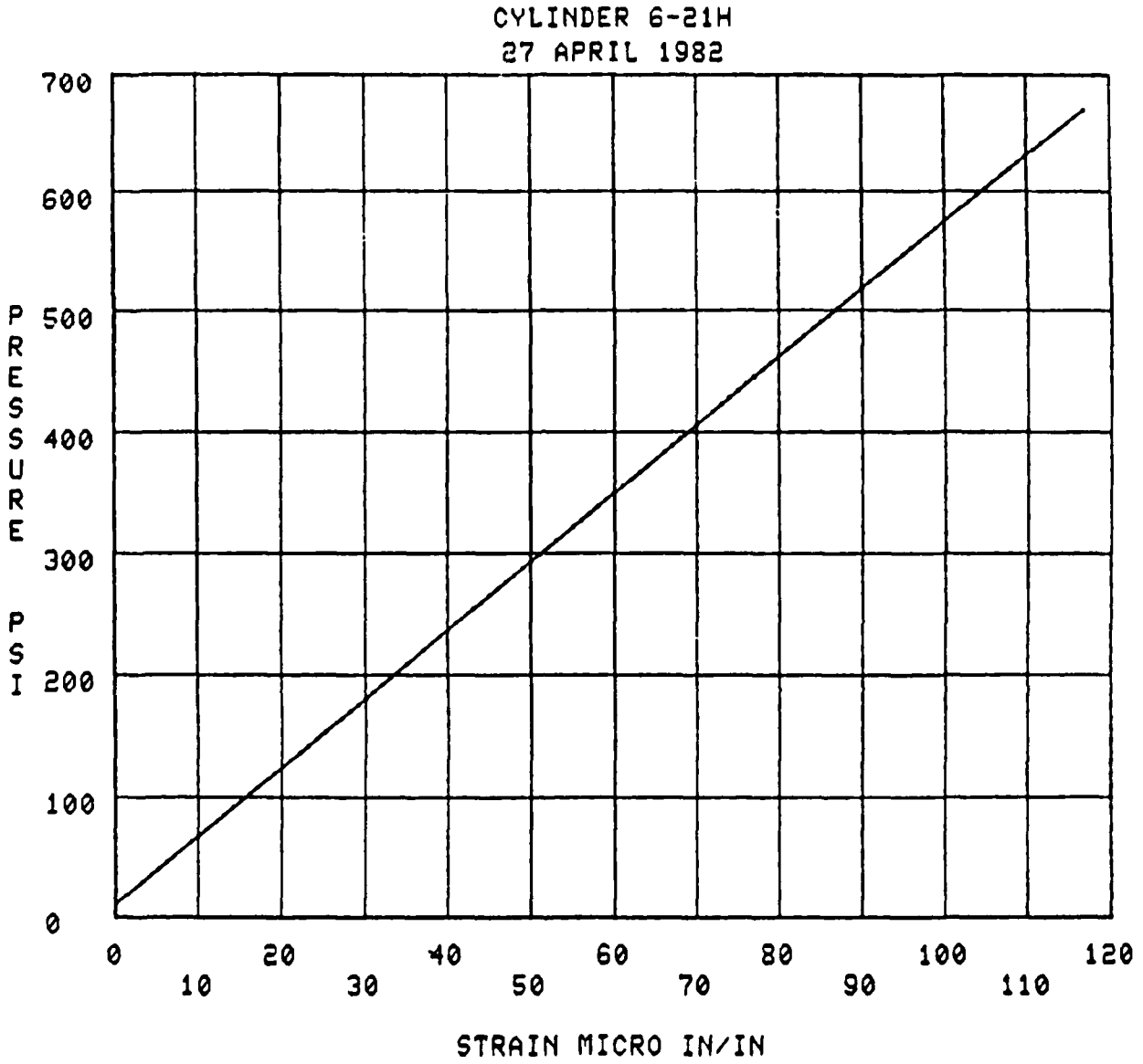
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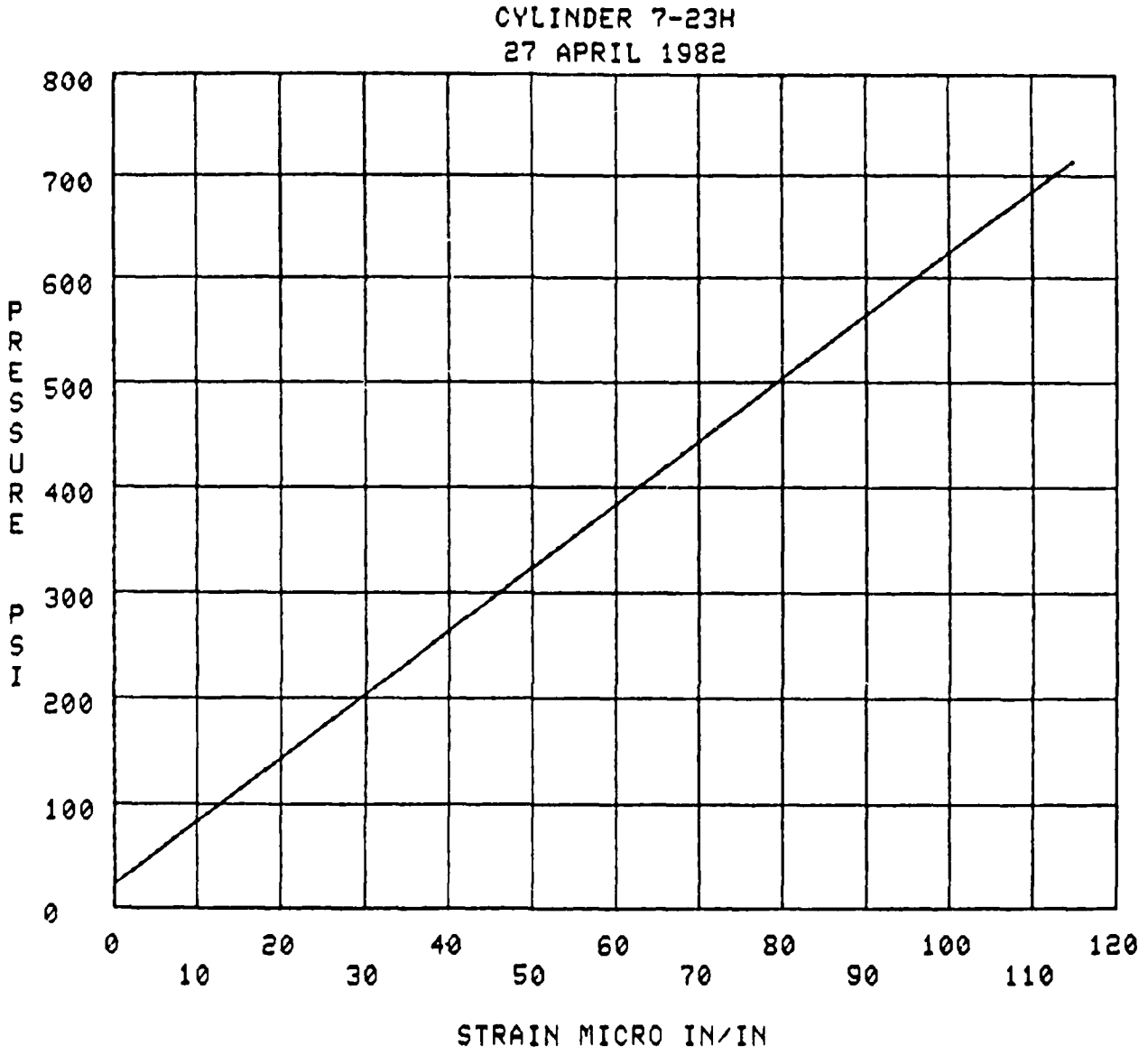
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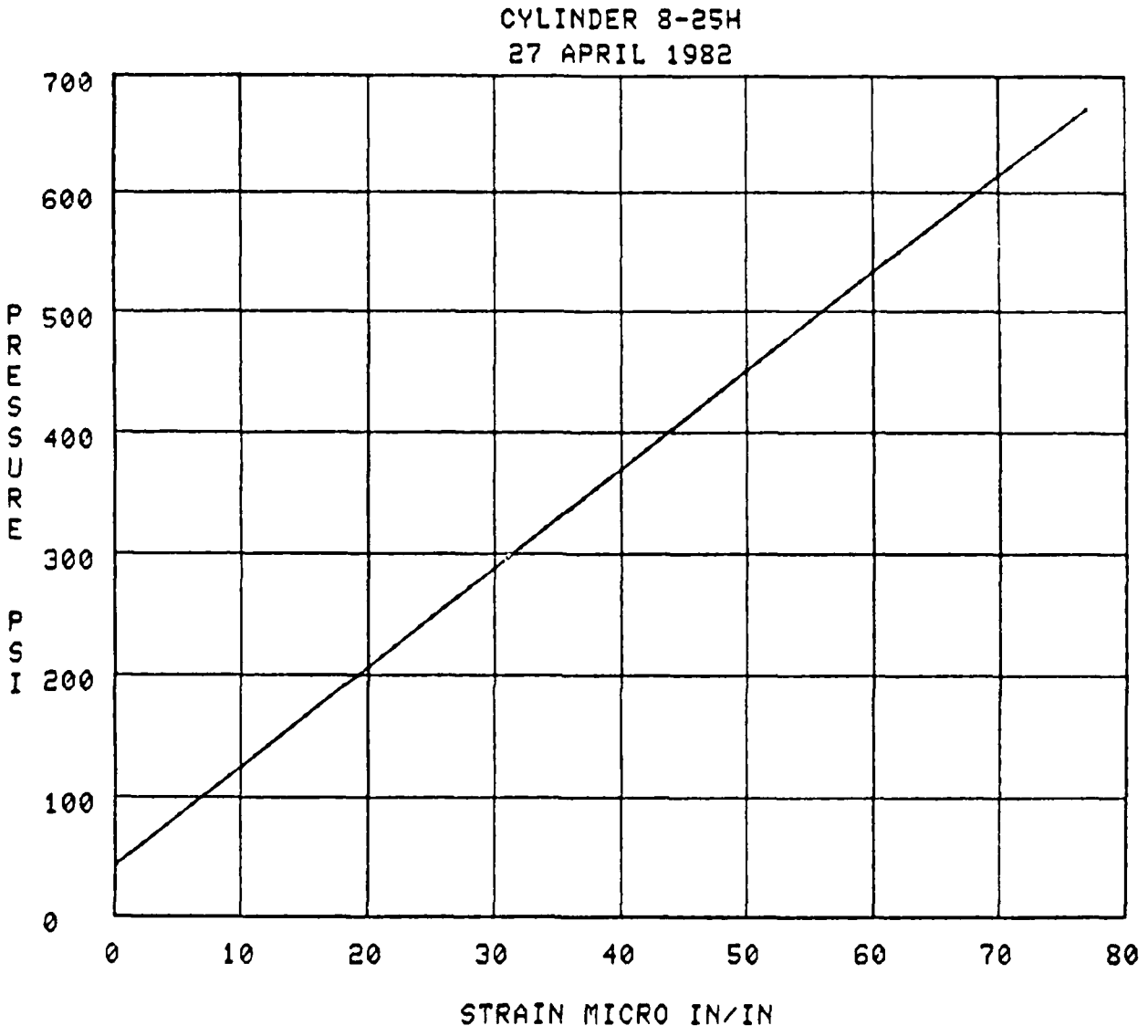
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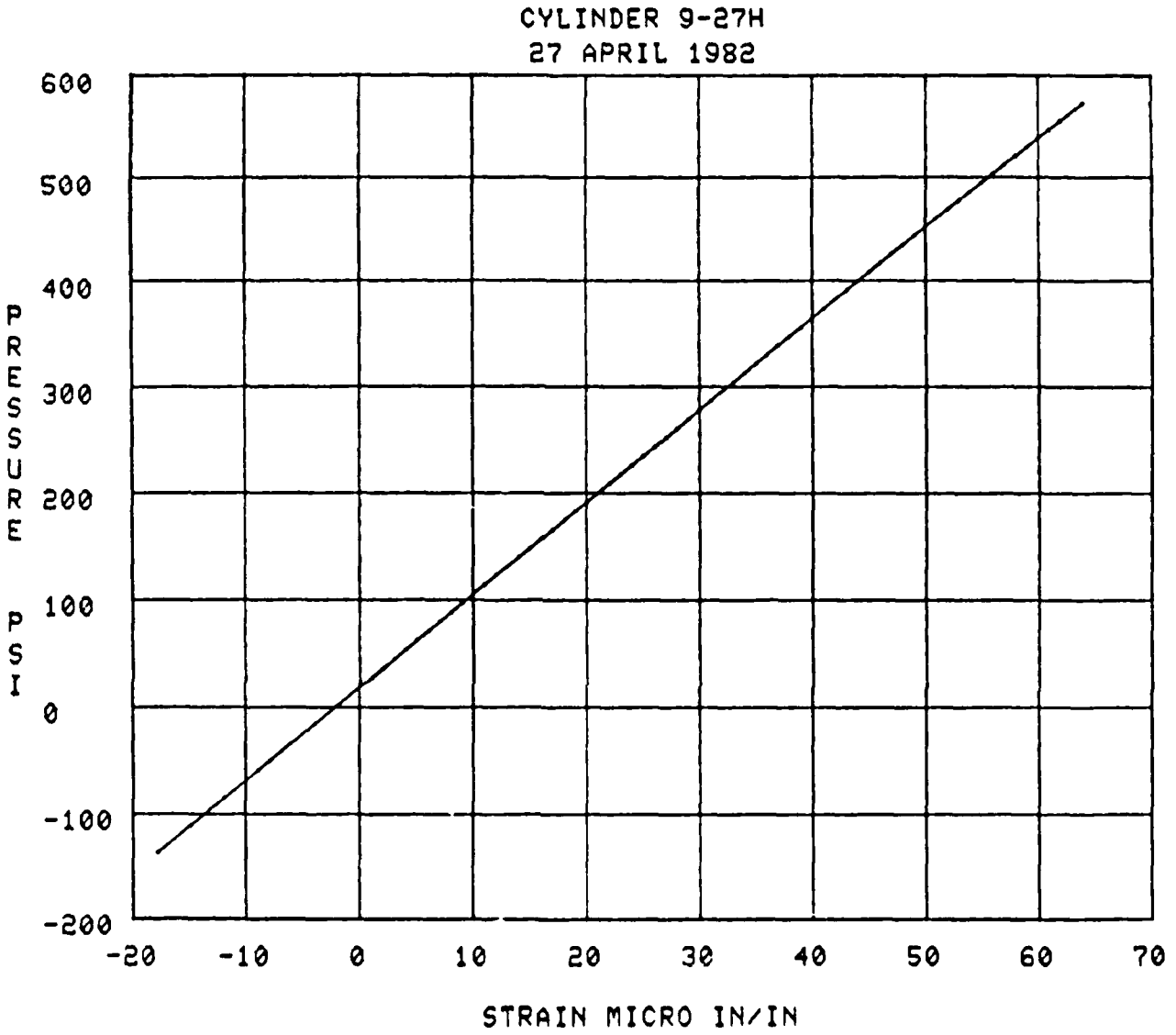
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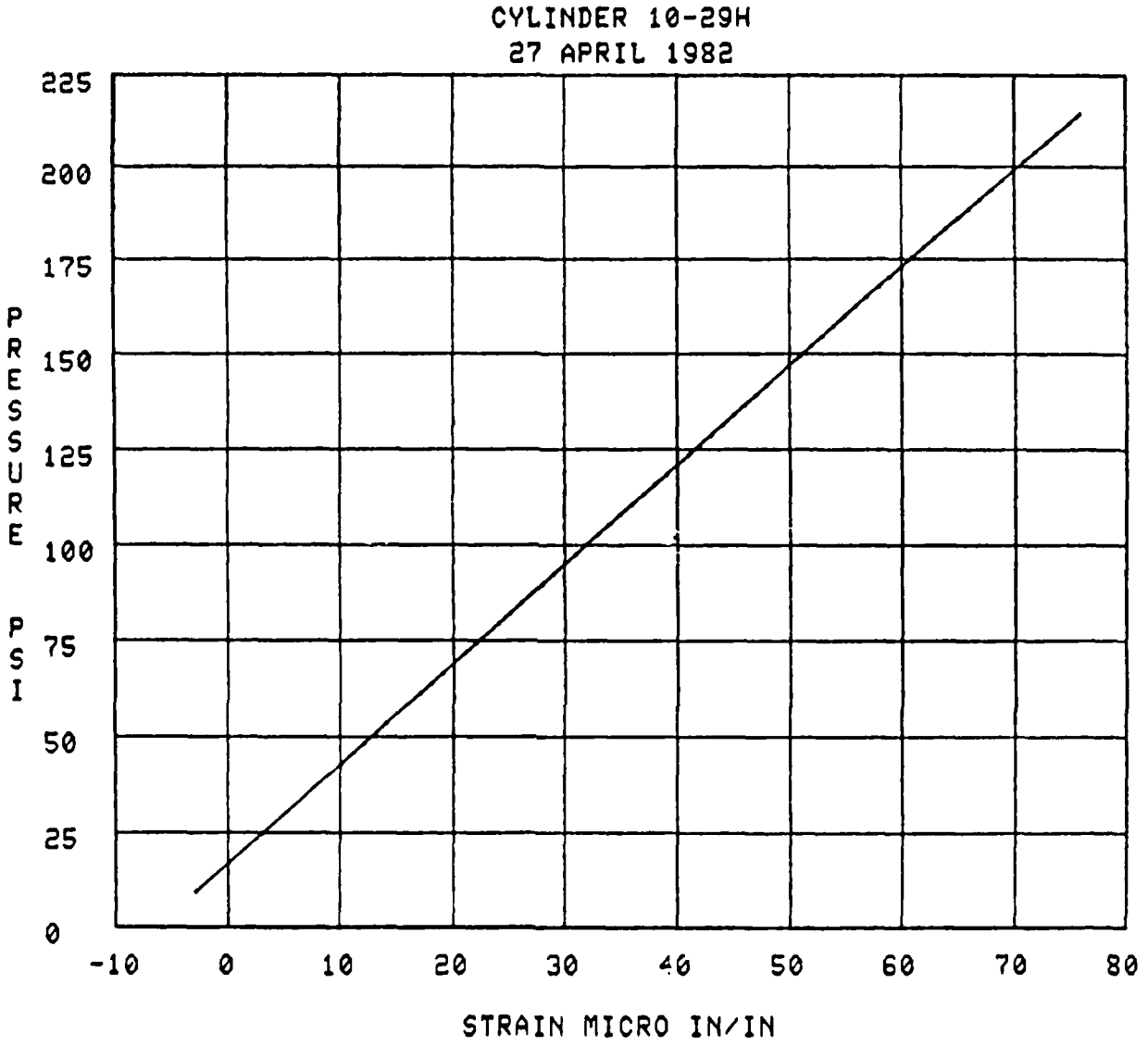
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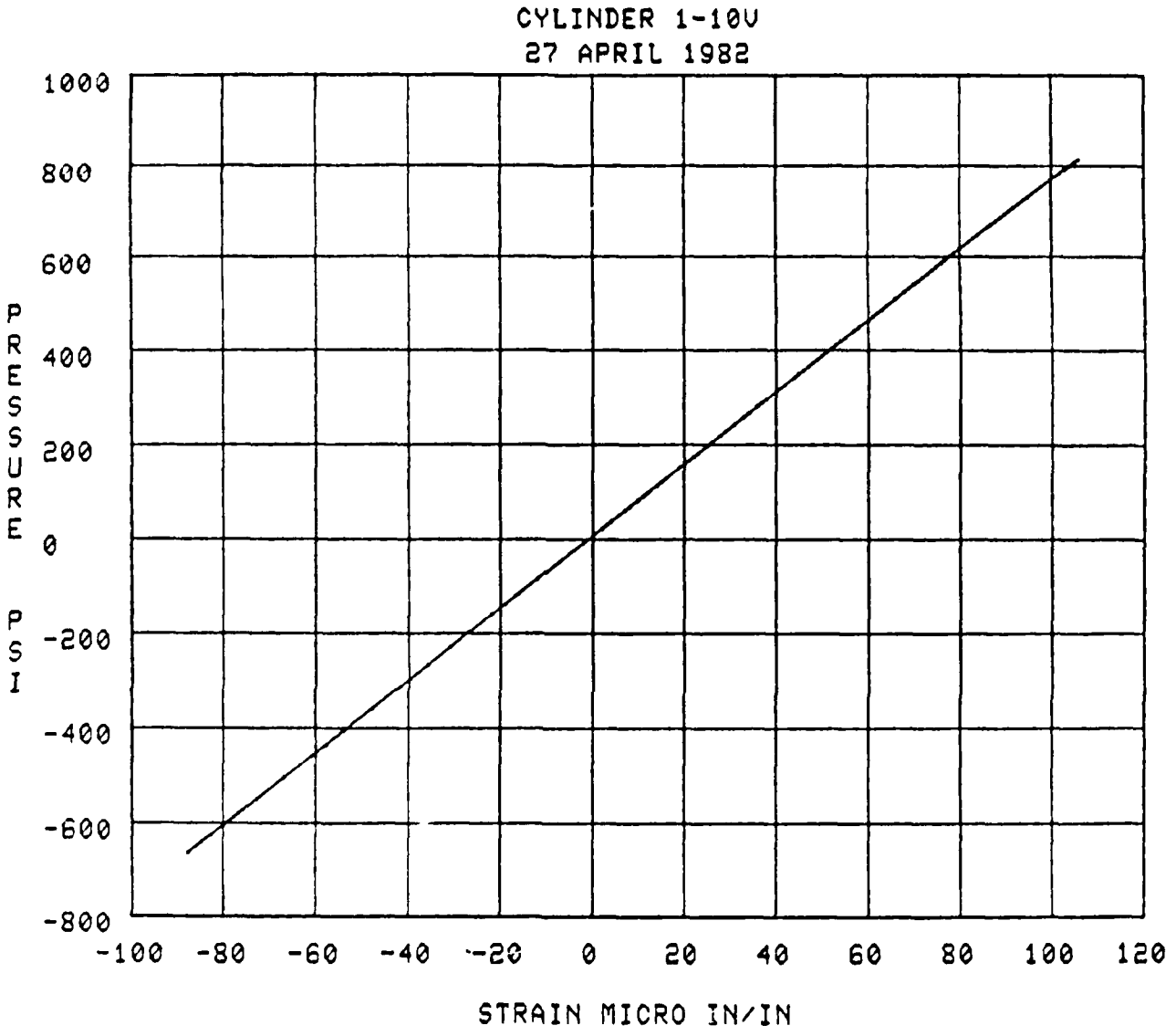
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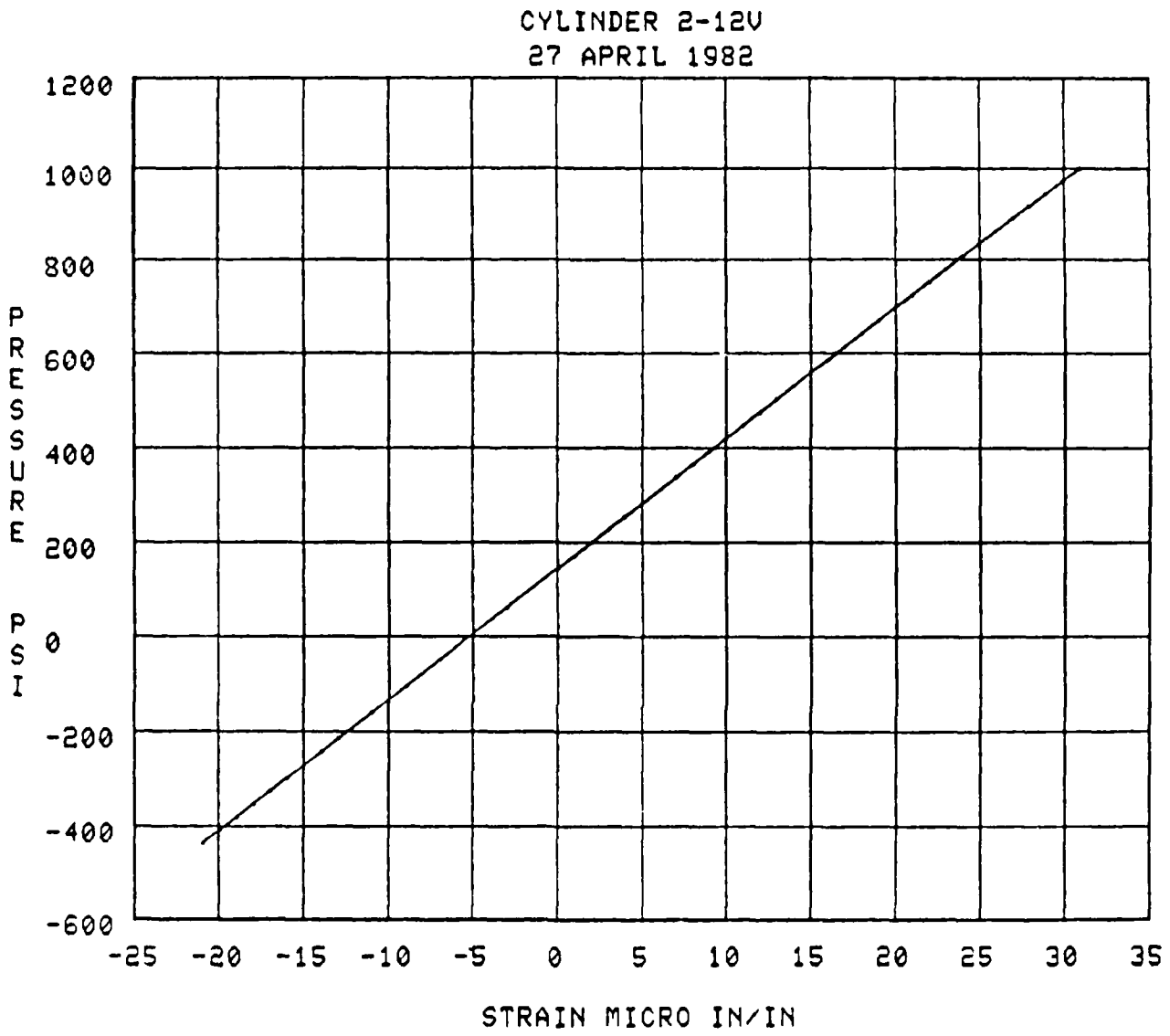
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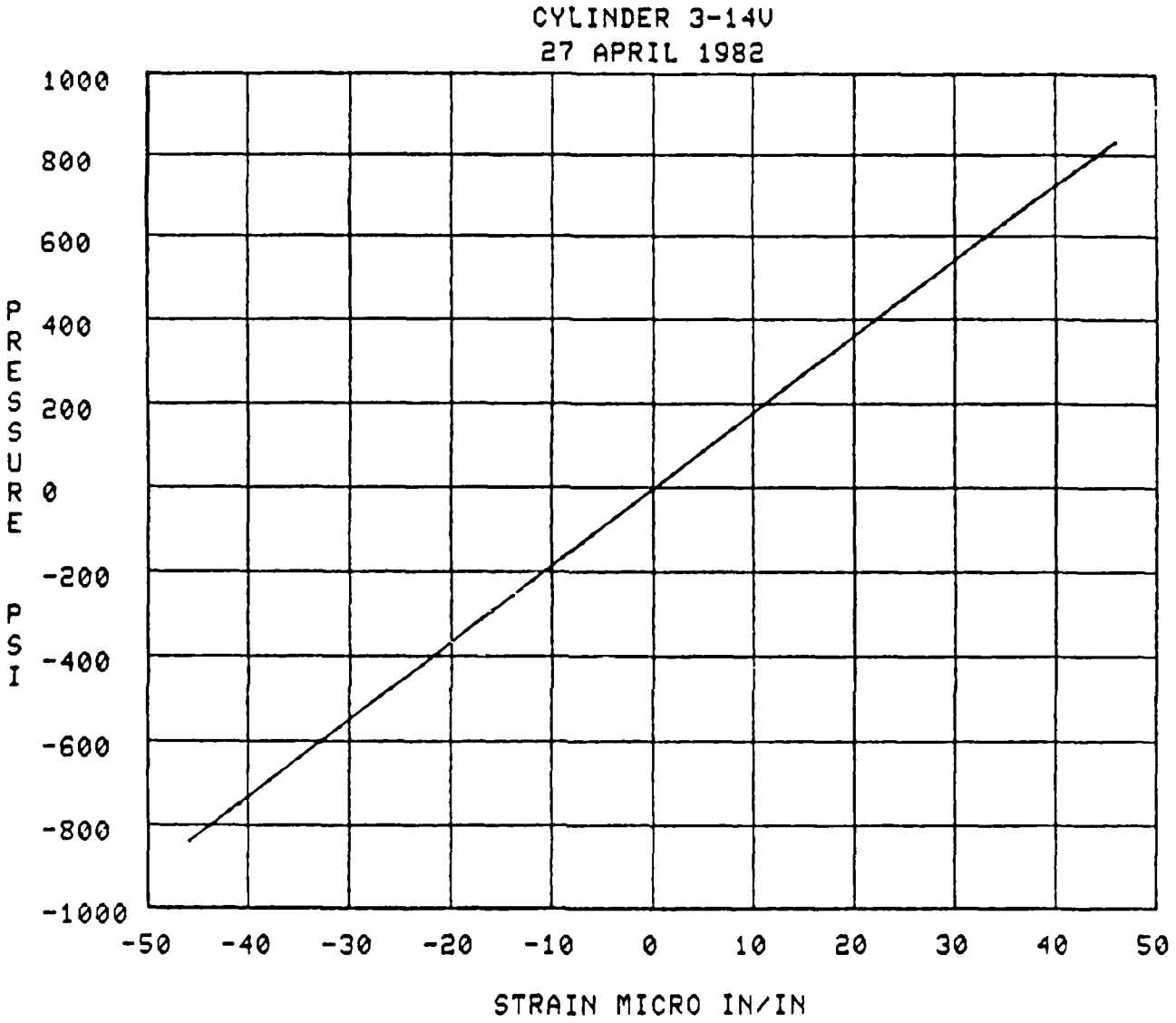
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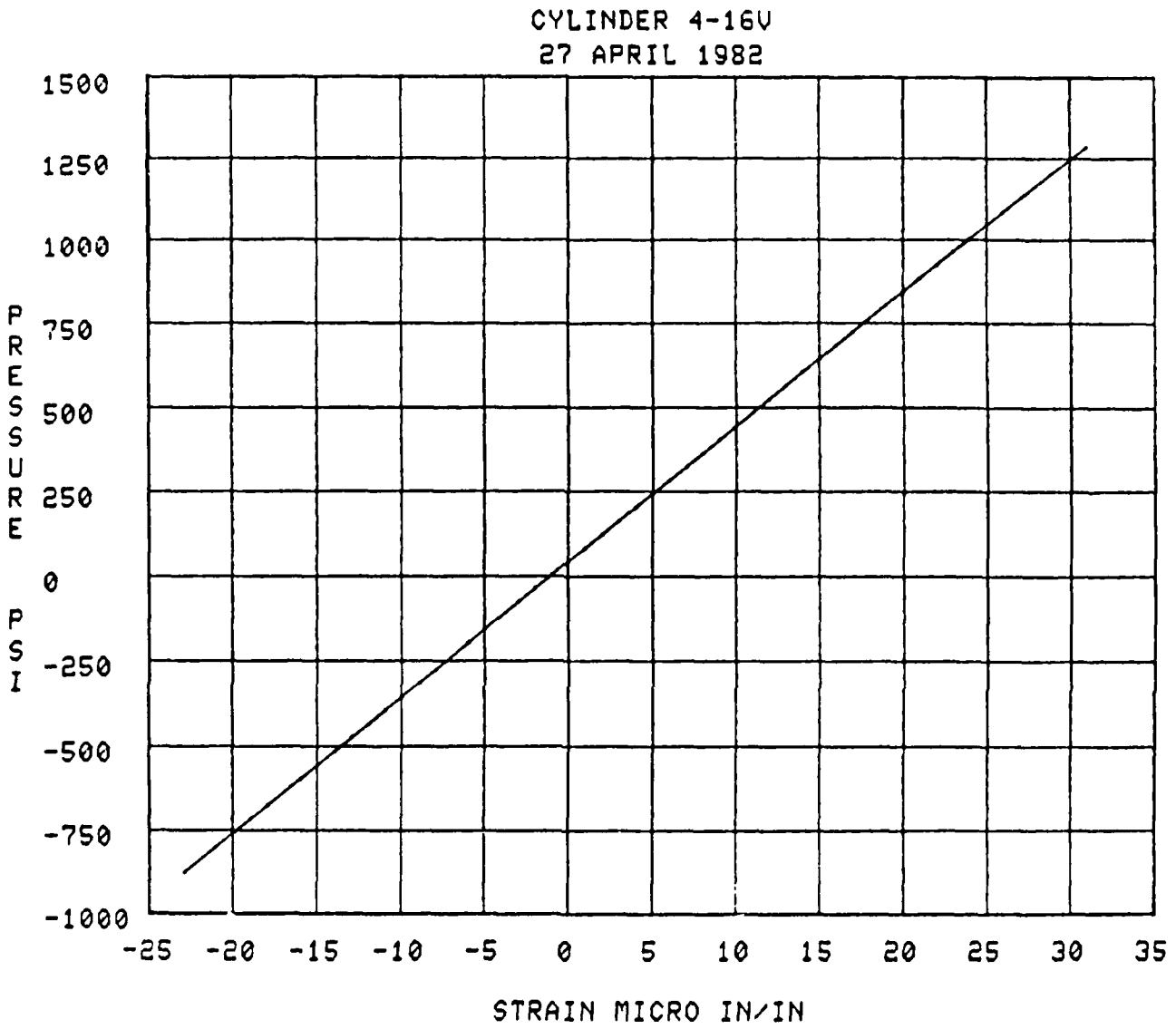
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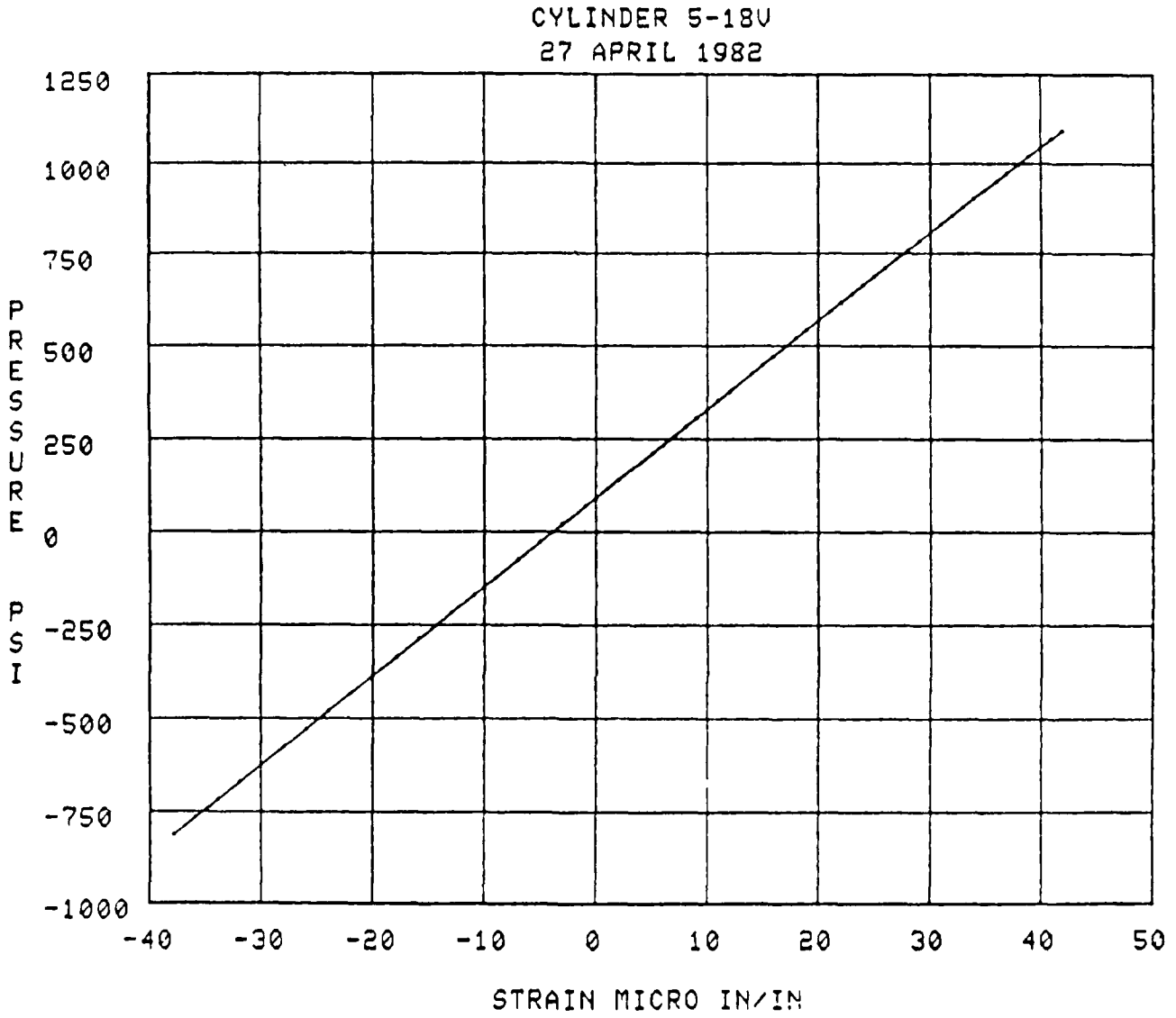
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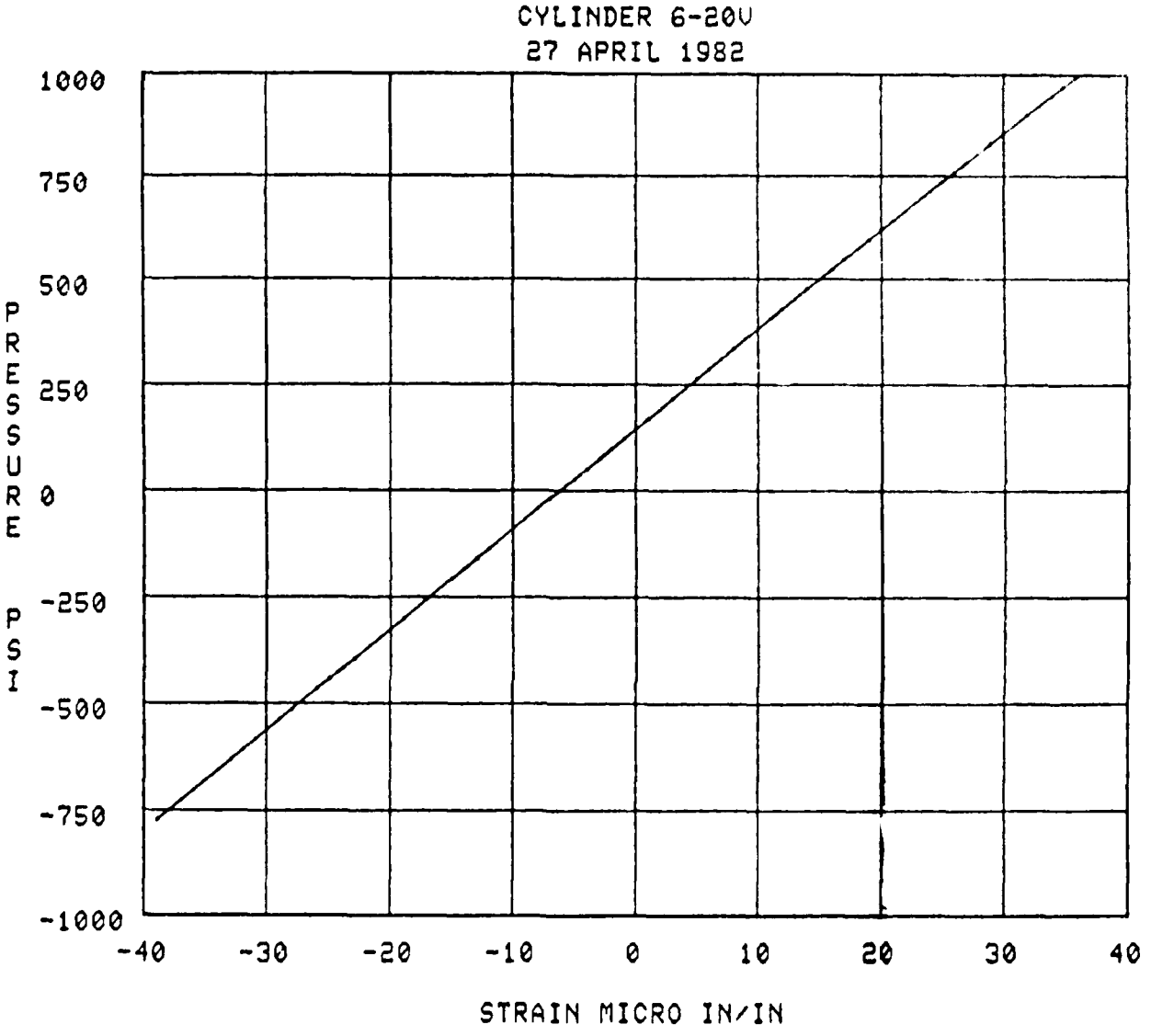
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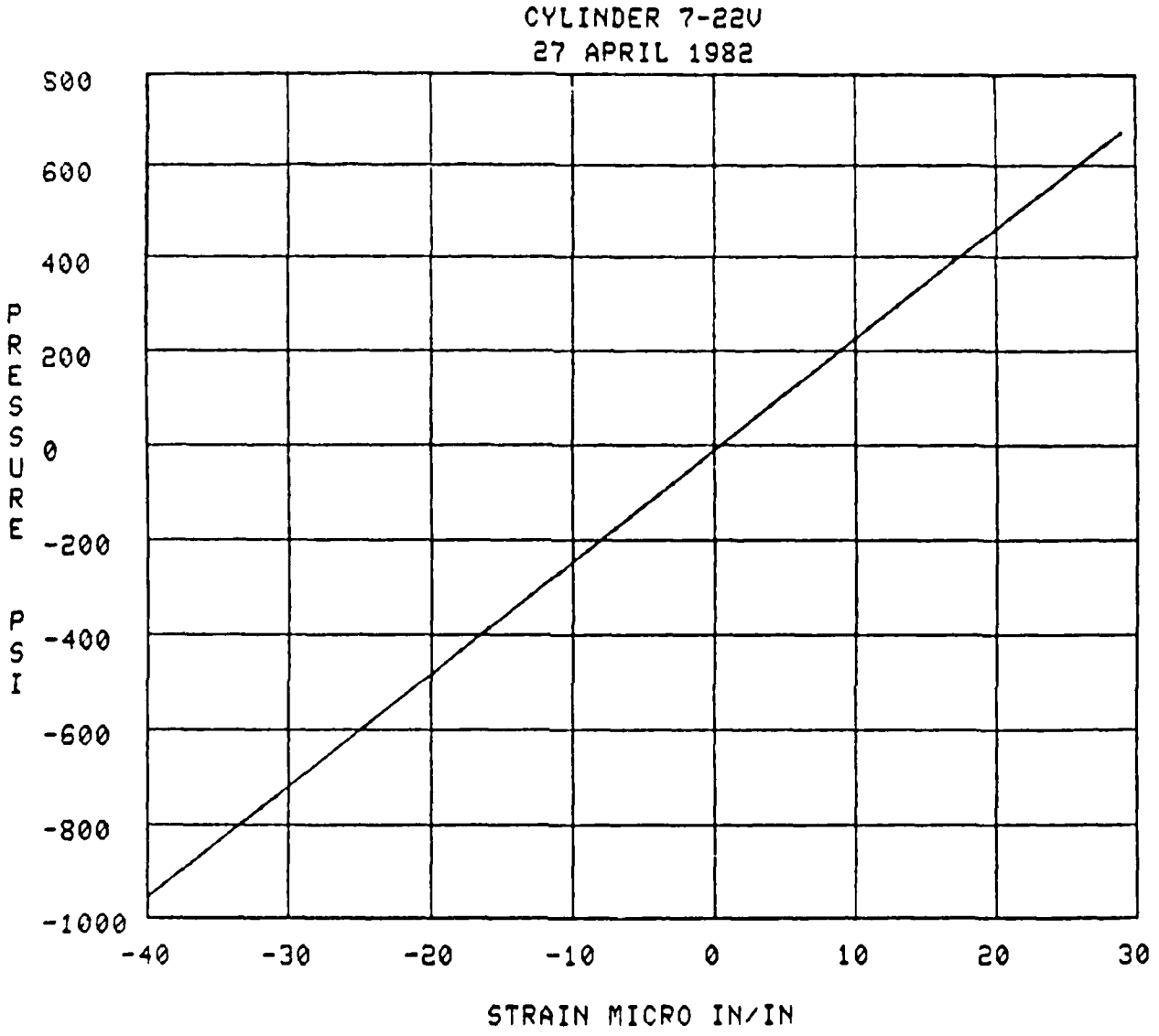
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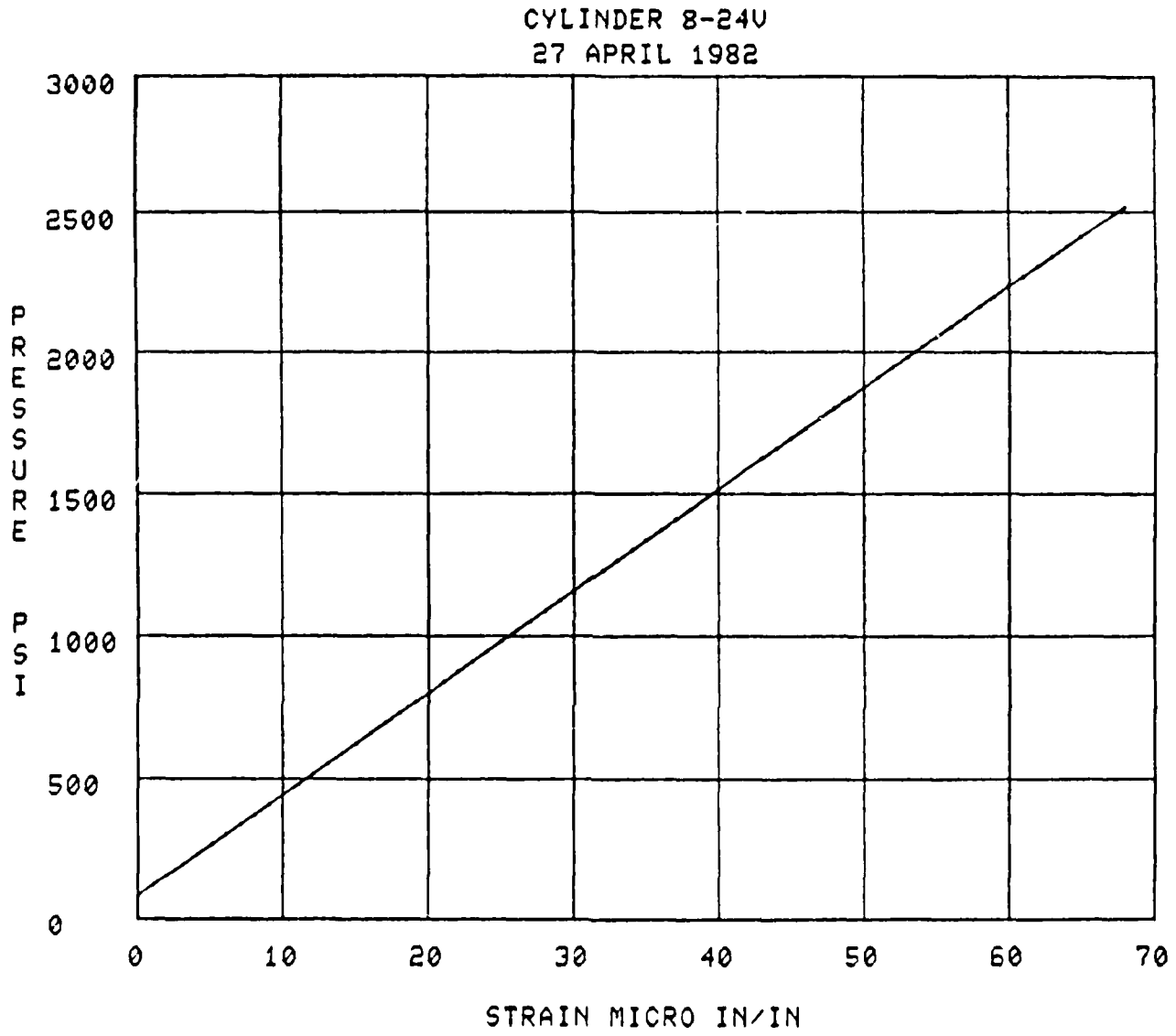
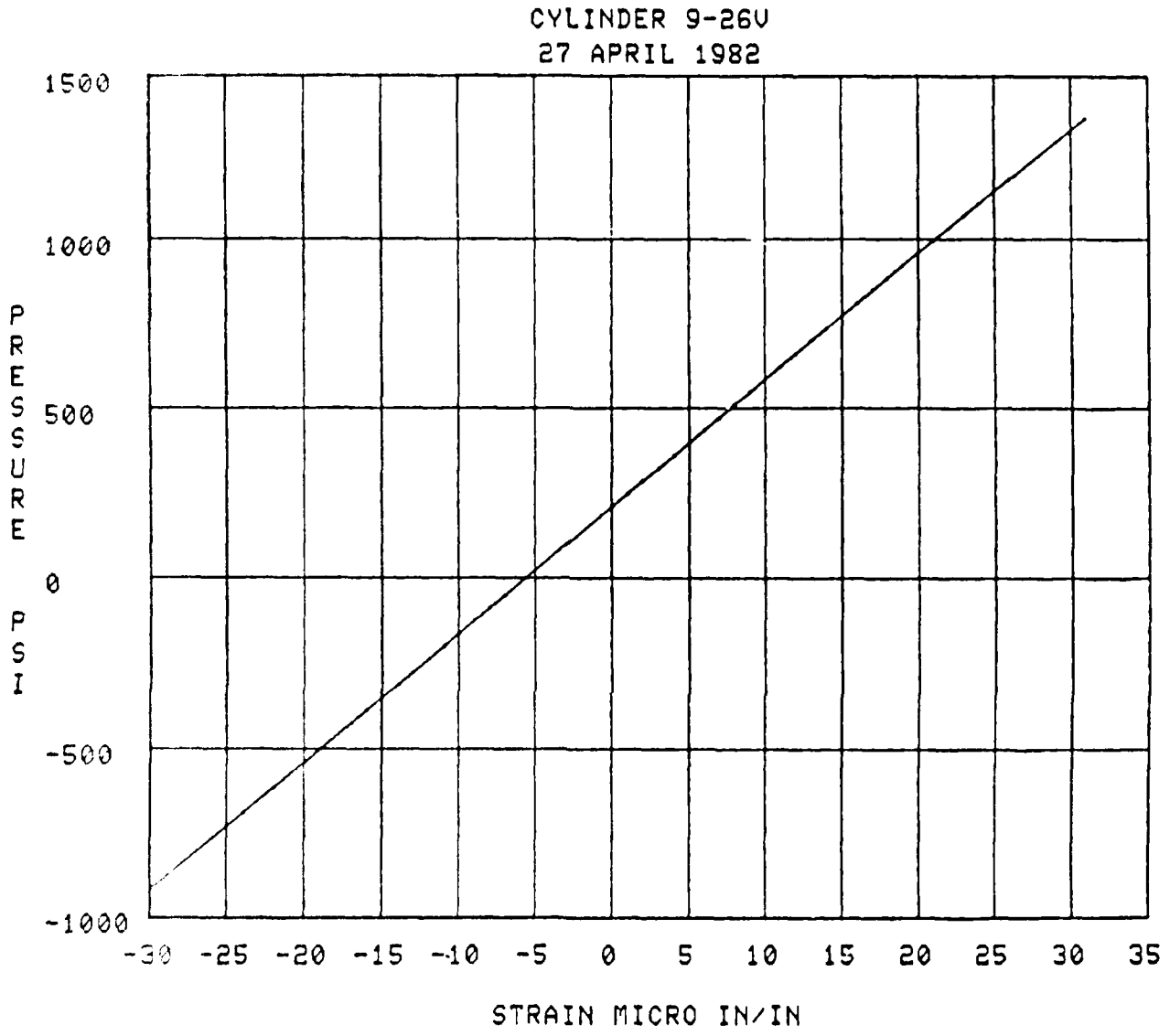
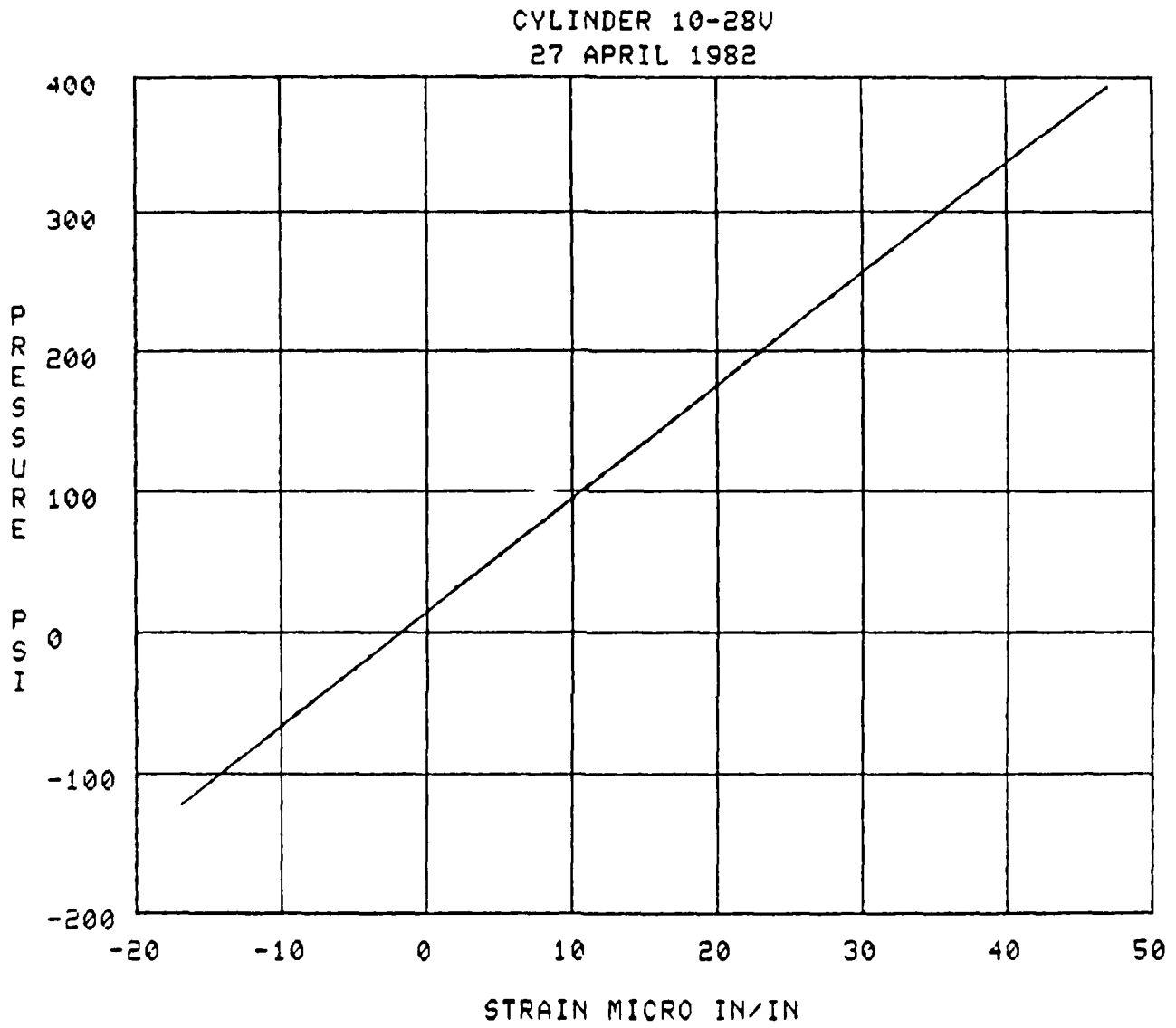
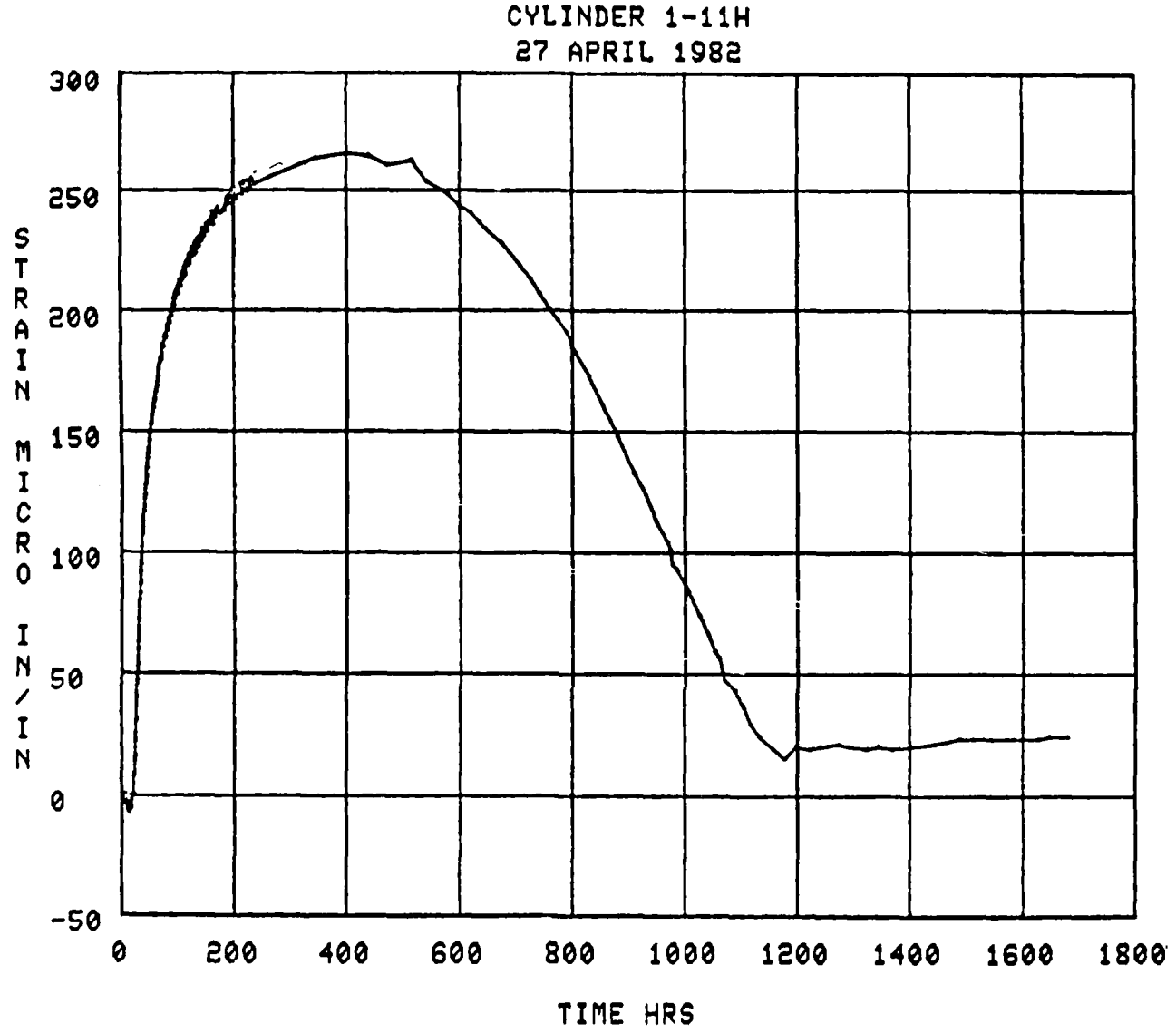
10
20
30
STRAIN MICRO IN/IN

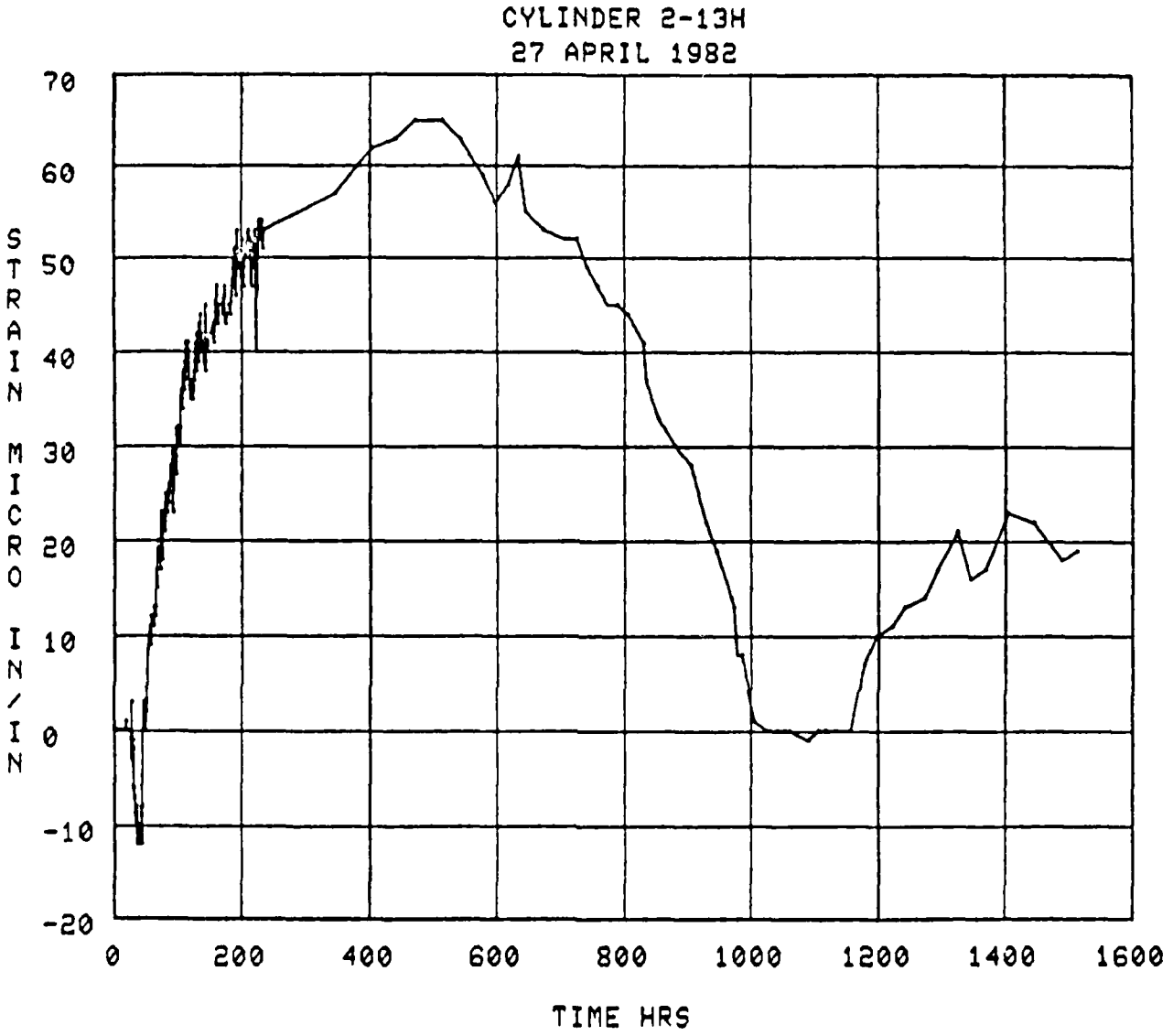

CYLINDER 8-24V
27 APRIL 1982
3000
2500
2000
1500
1000
500
0
PRESSURE PSI
0
10
20
30
40
50
60
70
STRAIN MICRO IN/IN

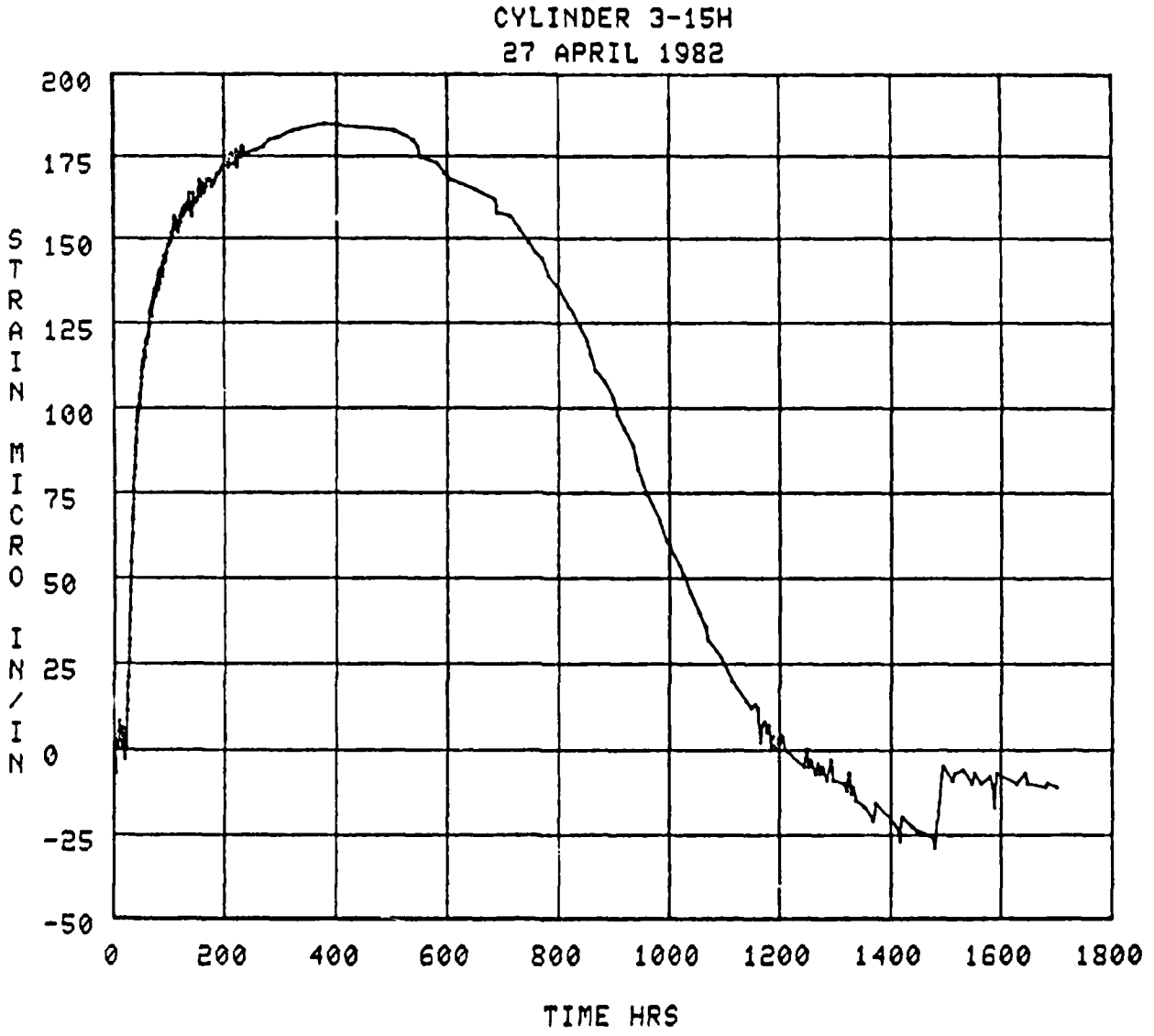

CYLINDER 9-26V
27 APRIL 1982
1500
1000
500
0
-500
-1000
PRESSURE PSI
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35
STRAIN MICRO IN/IN

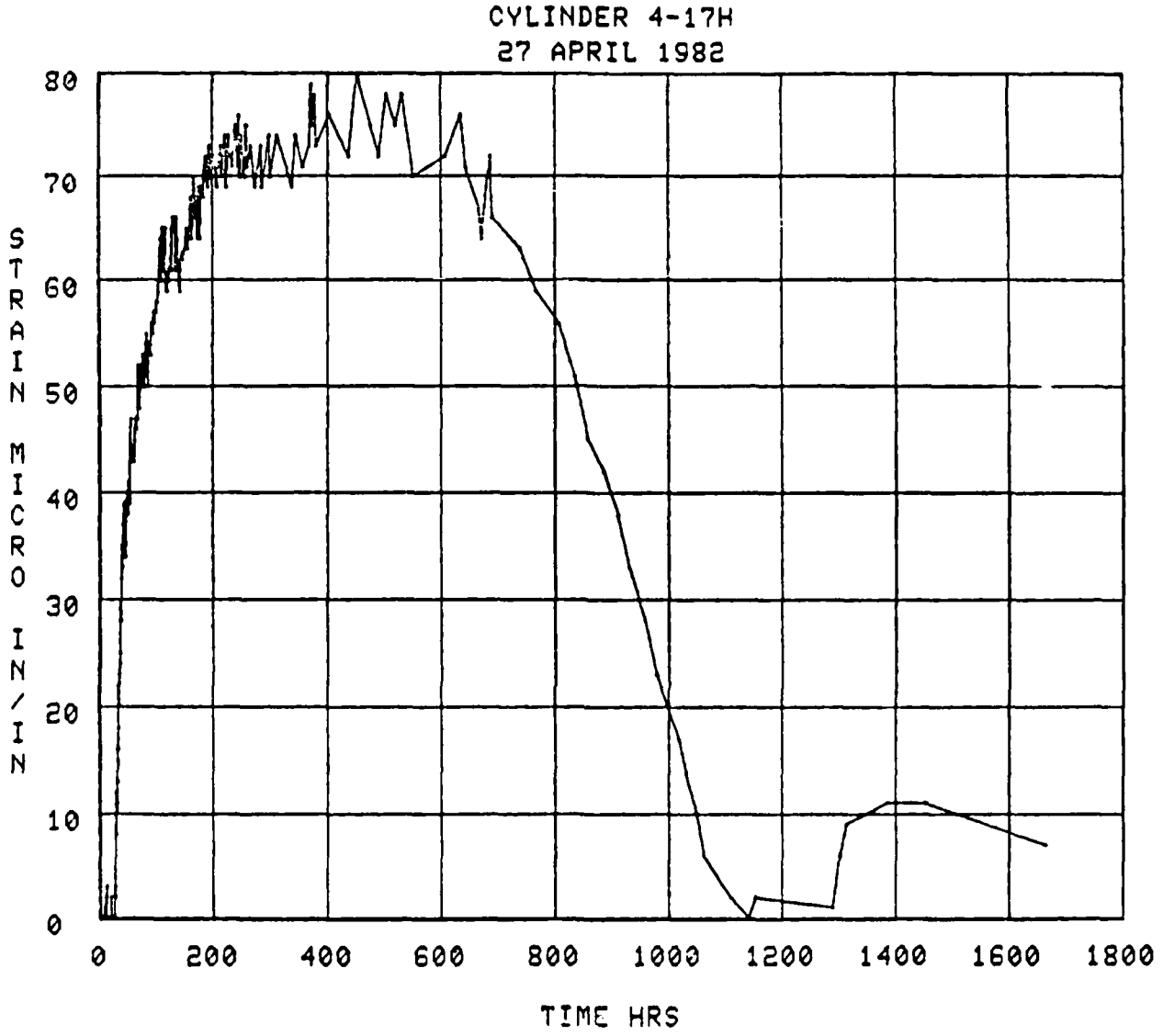

CYLINDER 10-28V
27 APRIL 1982
400
300
200
100
0
-100
-200
PRESSURE PSI
-20
-10
0
10
20
30
40
50
STRAIN MICRO IN/IN

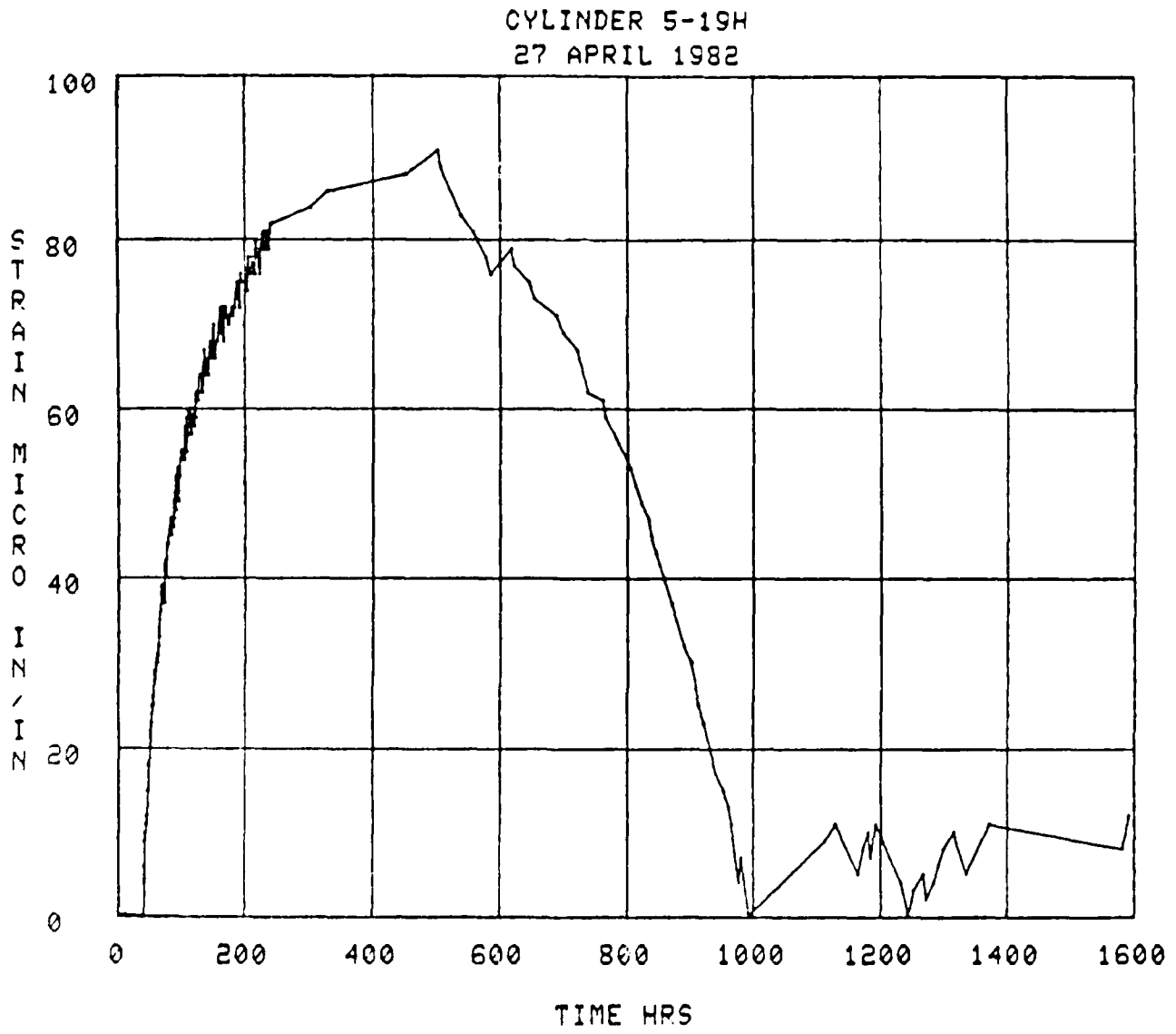
APPENDIX B: TANGENTIAL AND LONGITUDINAL STRAIN DATA

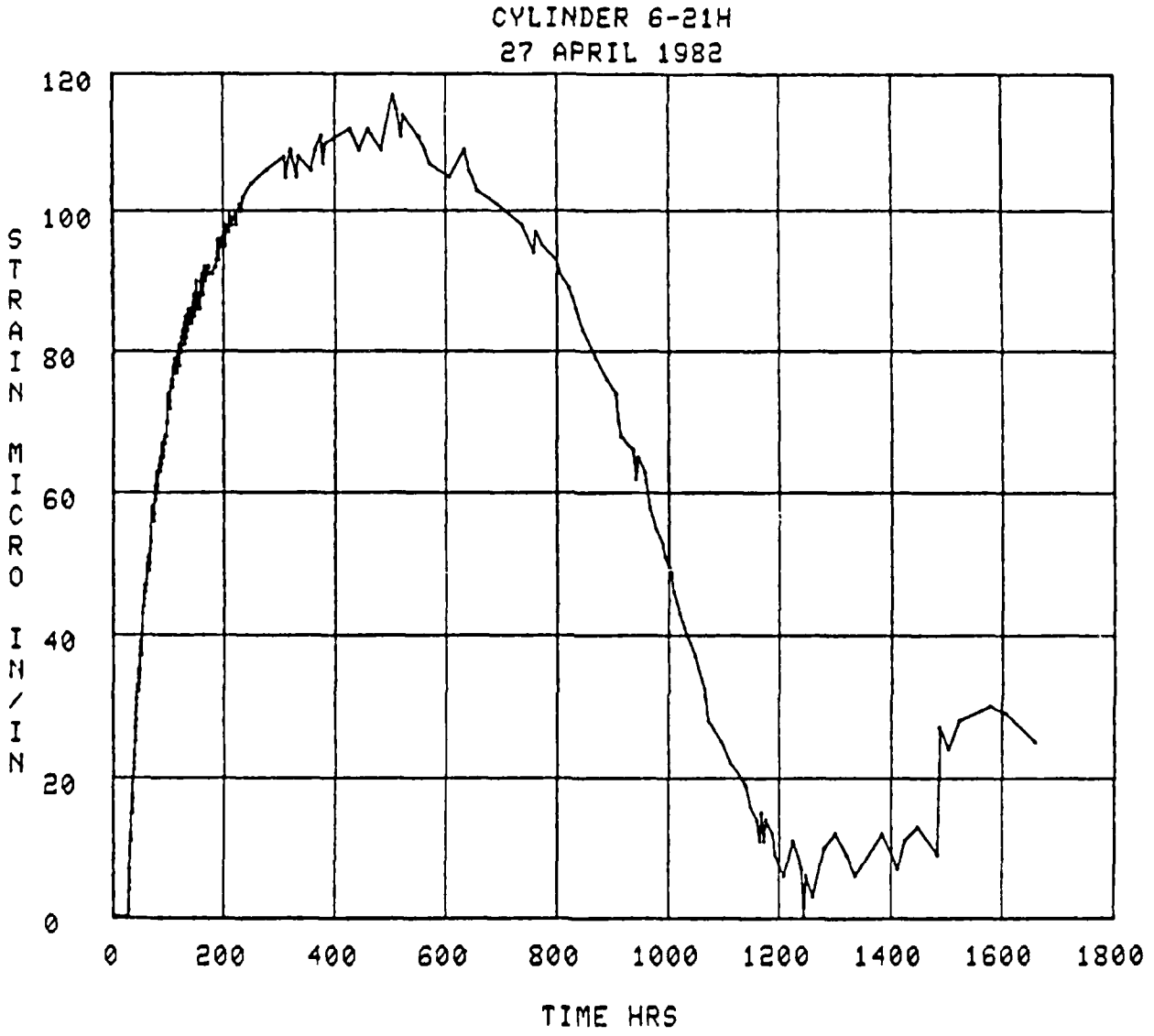

CYLINDER 1-11H
27 APRIL 1982
STRAIN MICRO IN/IN
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

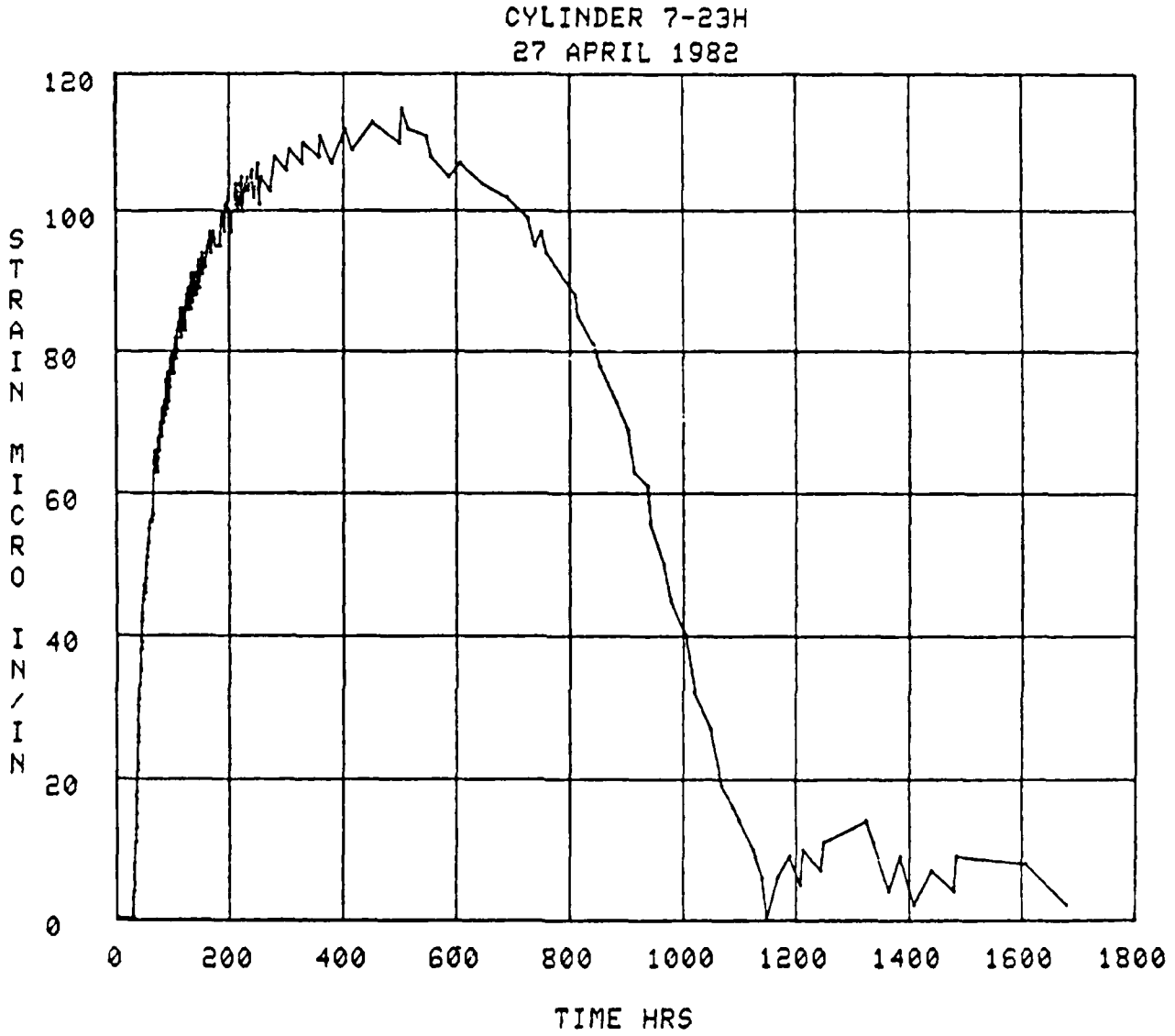

CYLINDER 2-13H
27 APRIL 1982
STRAIN MICRO IN/IN
70
60
50
40
30
20
10
0
-10
-20
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

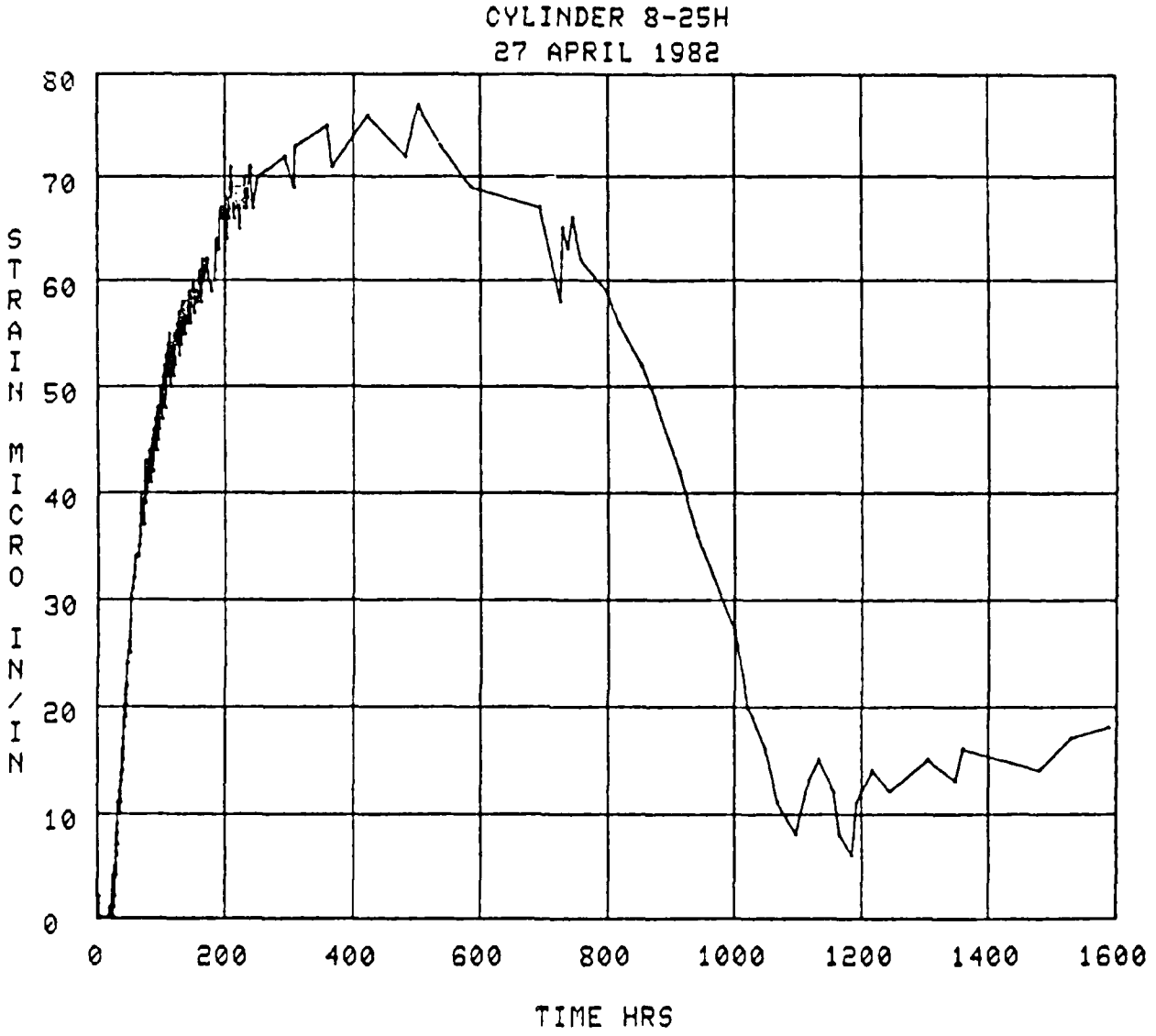

CYLINDER 3-15H
27 APRIL 1982
STRAIN MICRO IN/IN
200
175
150
125
100
75
50
25
0
-25
-50
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 4-17H
27 APRIL 1982
STRAIN MICRO IN/IN
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

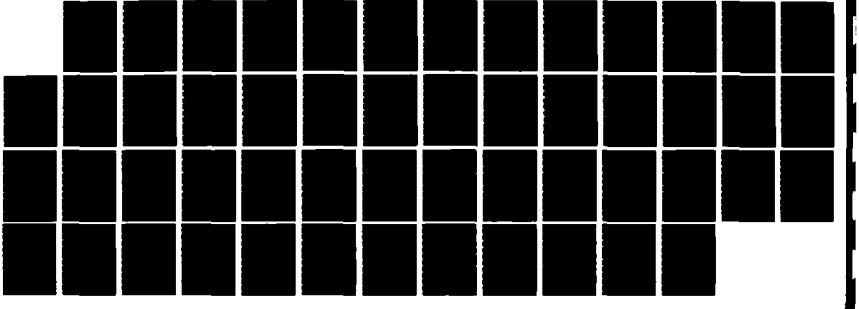

CYLINDER 5-19H
27 APRIL 1982
STRAIN MICRO IN/IN
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

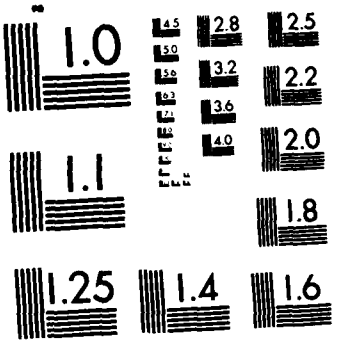

CYLINDER 6-21H
27 APRIL 1982
STRAIN MICRO IN/IN
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 7-23H
27 APRIL 1982
STRAIN MICRO IN/IN
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

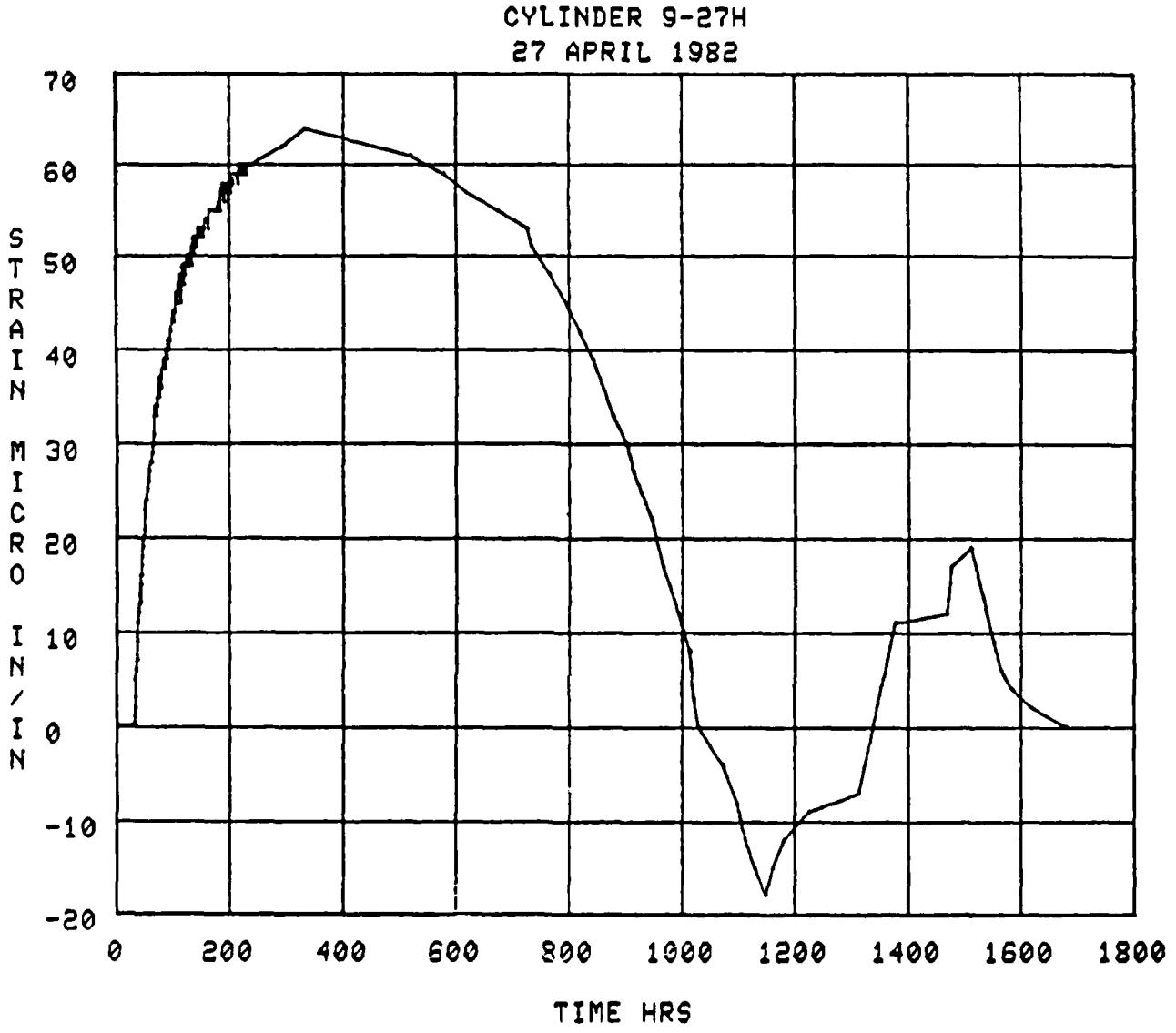

CYLINDER 8-25H
27 APRIL 1982
STRAIN MICRO IN/IN
0
10
20
30
40
50
60
70
80
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

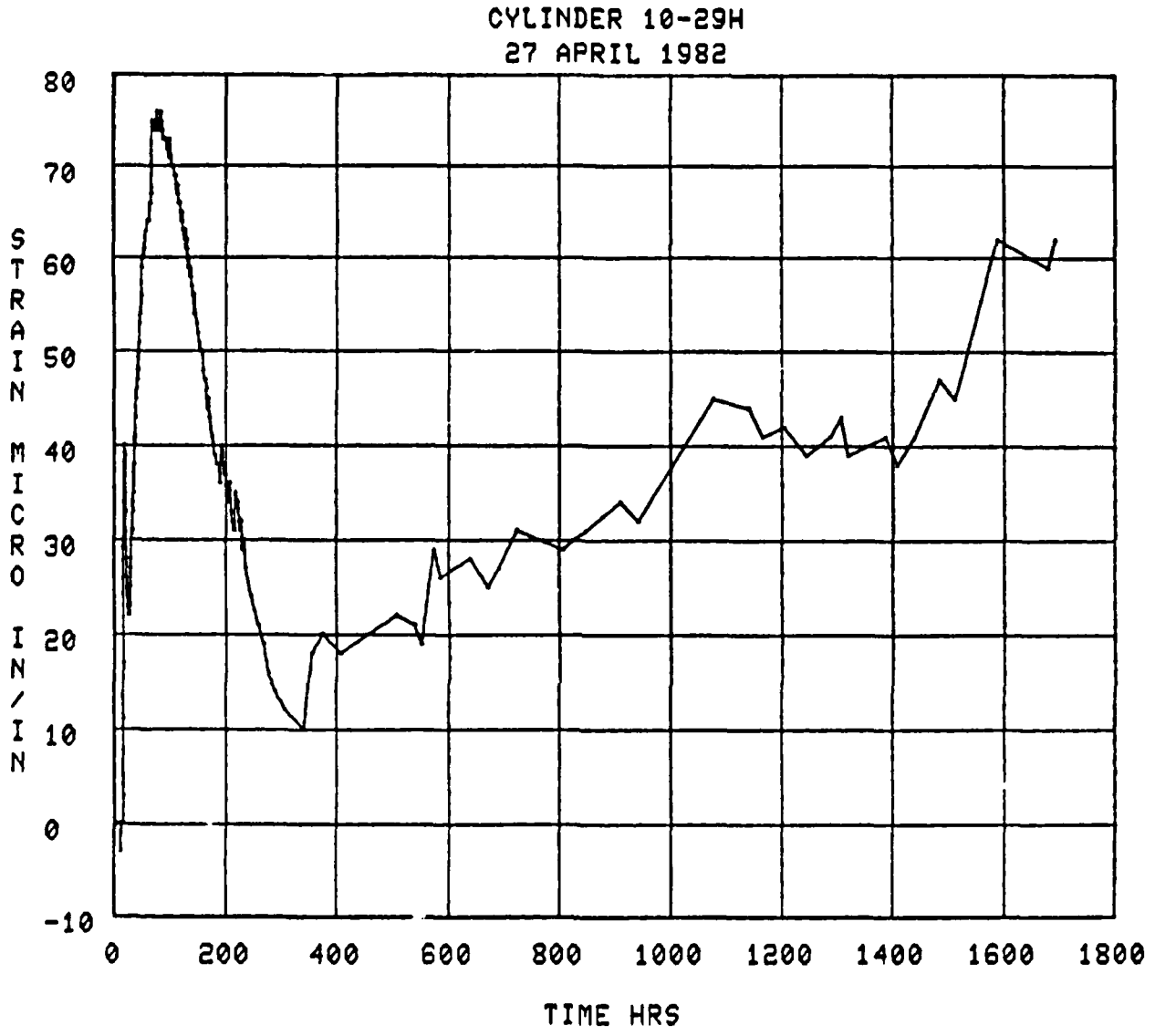
AD-A163 009 EXPANSIVE GROUT PLUG EFFECTS IN RESTRAINED ENVIRONMENTS 2/2
(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG MS STRUCTURES LAB C E PACE ET AL OCT 85
UNCLASSIFIED WES/TR/SL-85-9 F/G 13/2 NL

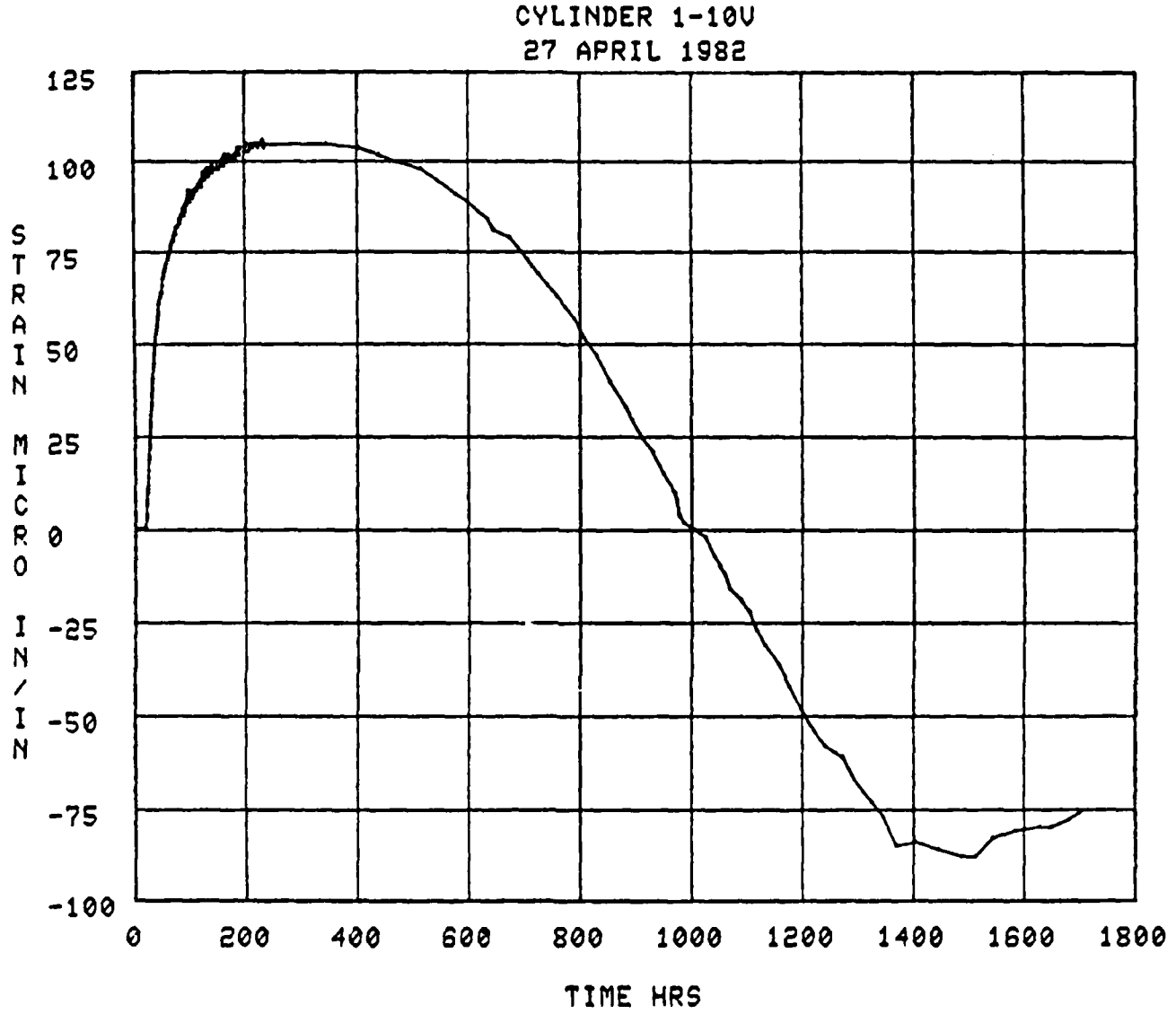


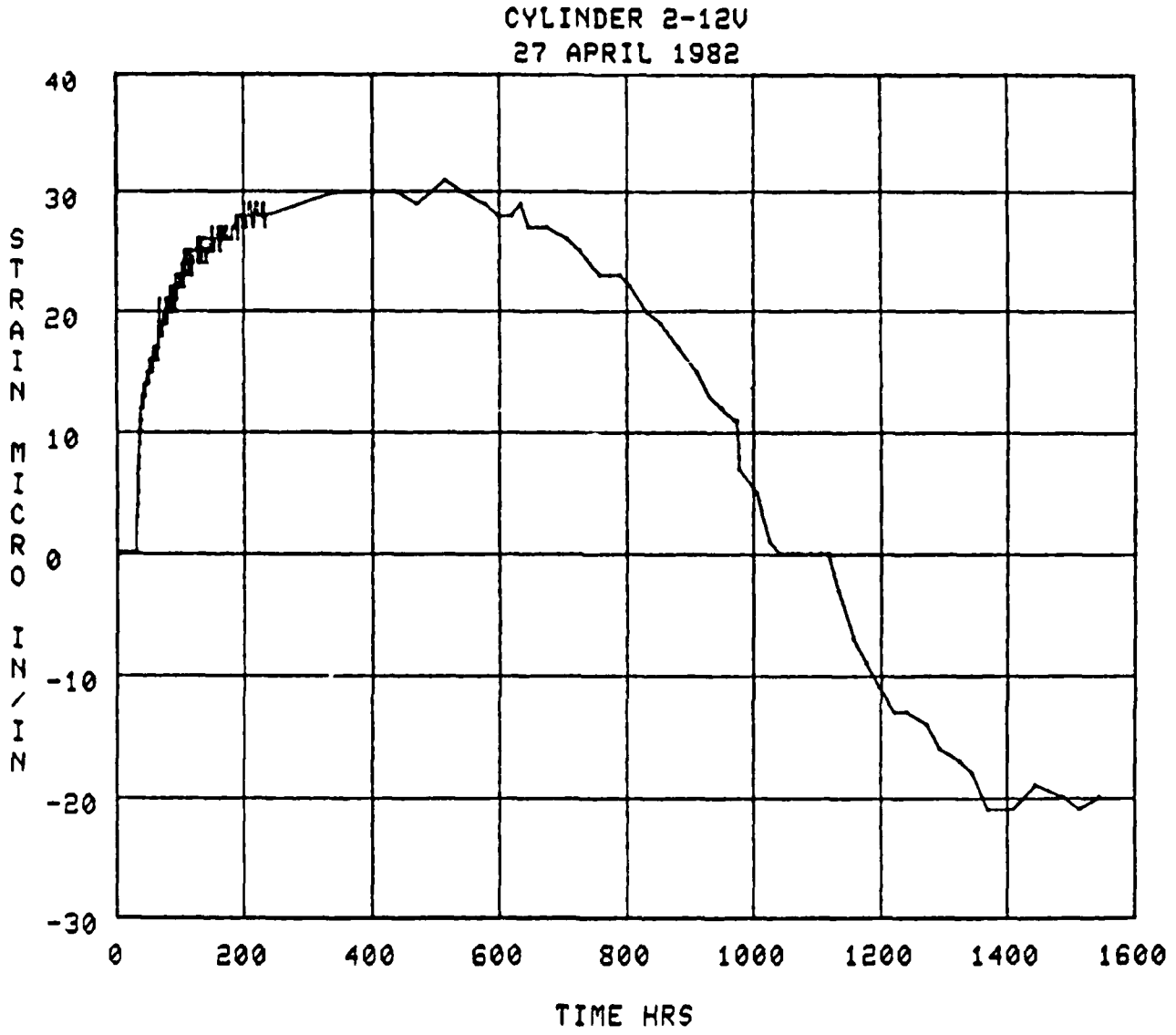


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


CYLINDER 9-27H
27 APRIL 1982
STRAIN MICRO IN/IN
70
60
50
40
30
20
10
0
-10
-20
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 10-29H
27 APRIL 1982
STRAIN MICRO IN/IN
80
70
60
50
40
30
20
10
0
-10
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 1-10V
27 APRIL 1982
125
100
75
50
25
0
-25
-50
-75
-100
STRAIN MICRO IN/IN
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 2-12V
27 APRIL 1982
STRAIN MICRO IN/IN
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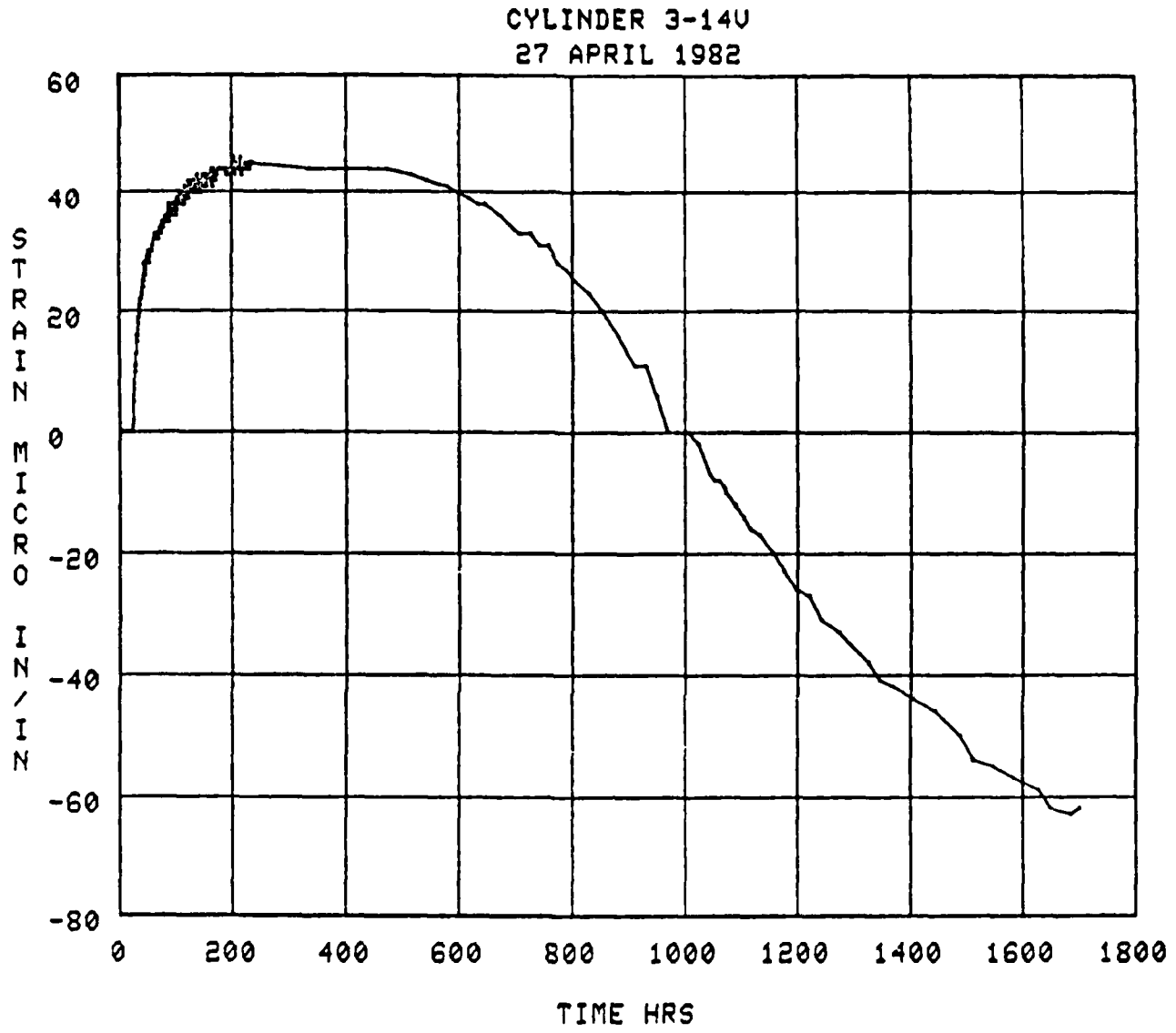
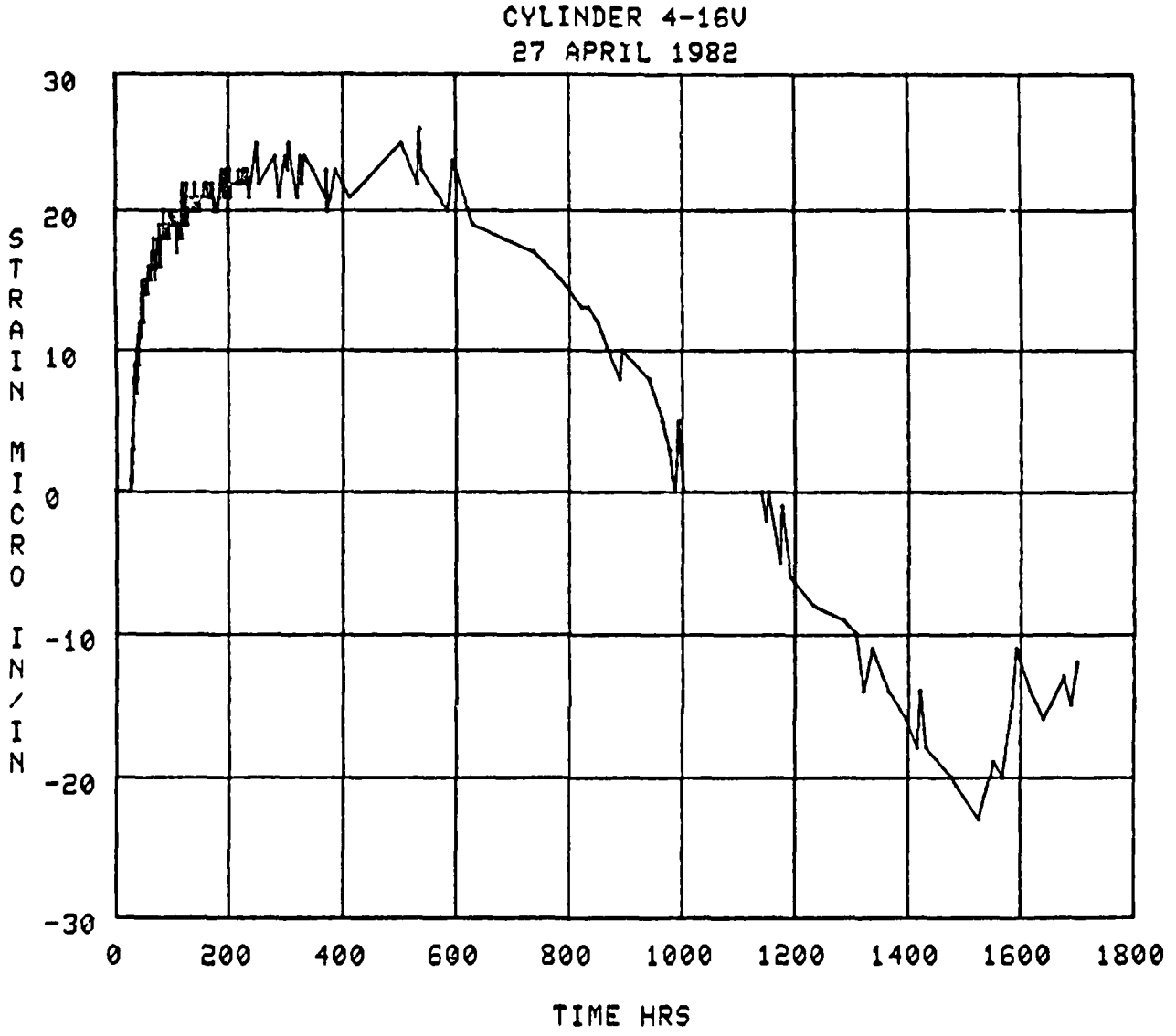
30
20
10
0
-10
-20
-30
0
200
400
600
800
1000
1200
1400
1600
TIME HRS


CYLINDER 3-14U
27 APRIL 1982
STRAIN MICRO IN/IN
60
40
20
0
-20
-40
-60
-80
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 4-16V
27 APRIL 1982
STRAIN MICRO IN/IN
30
20
10
0
-10
-20
-30
0
200
400
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800
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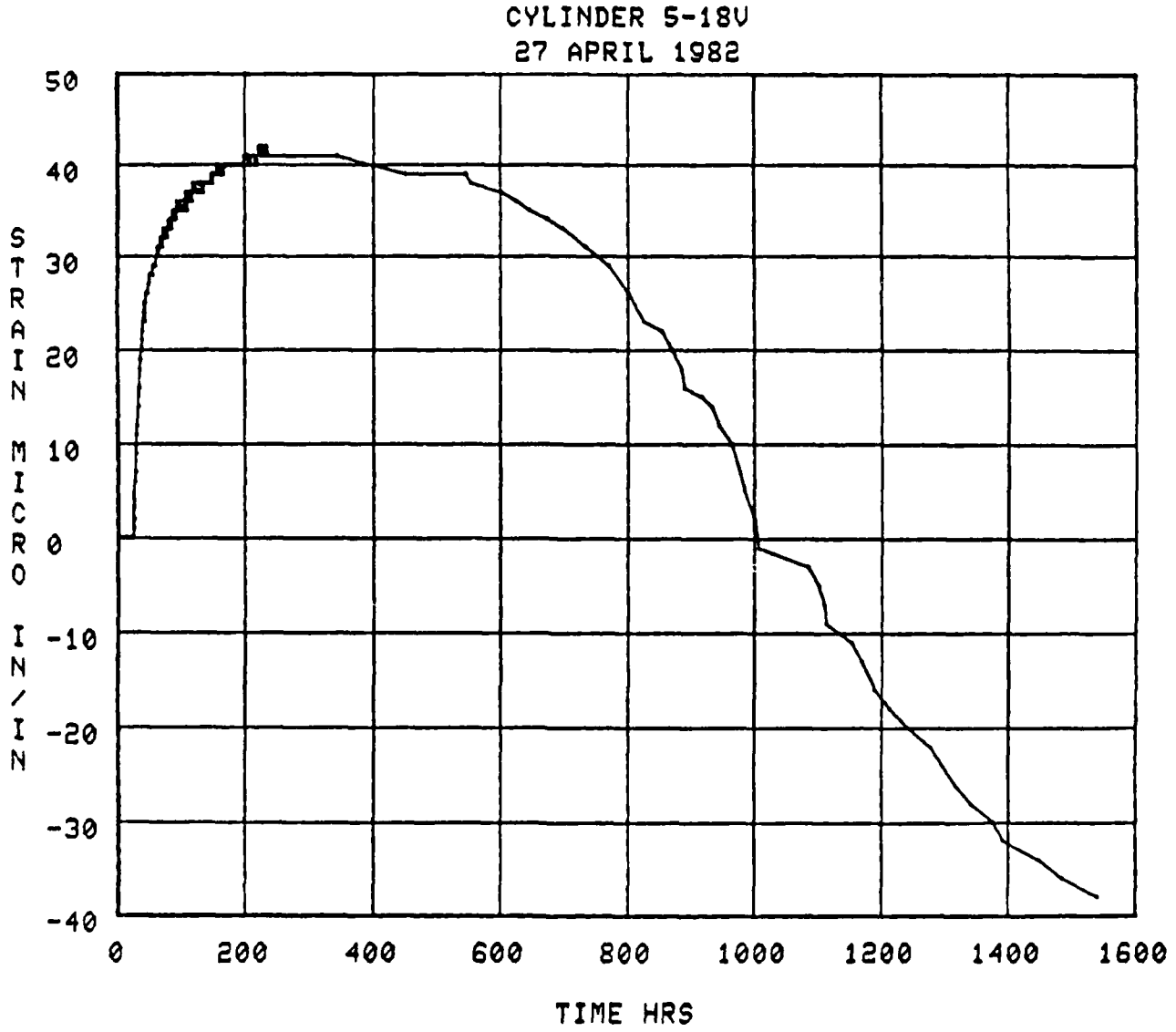
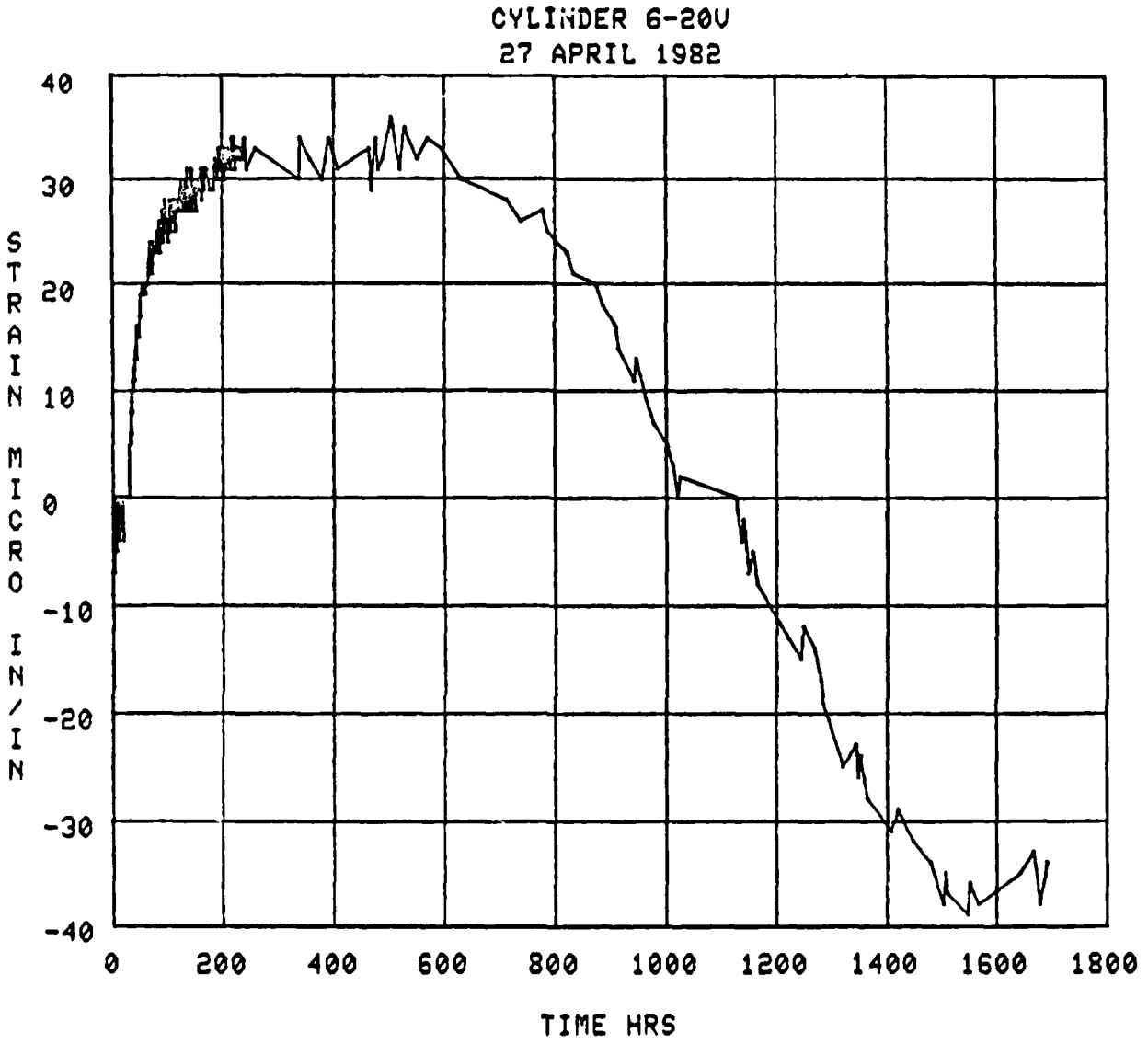
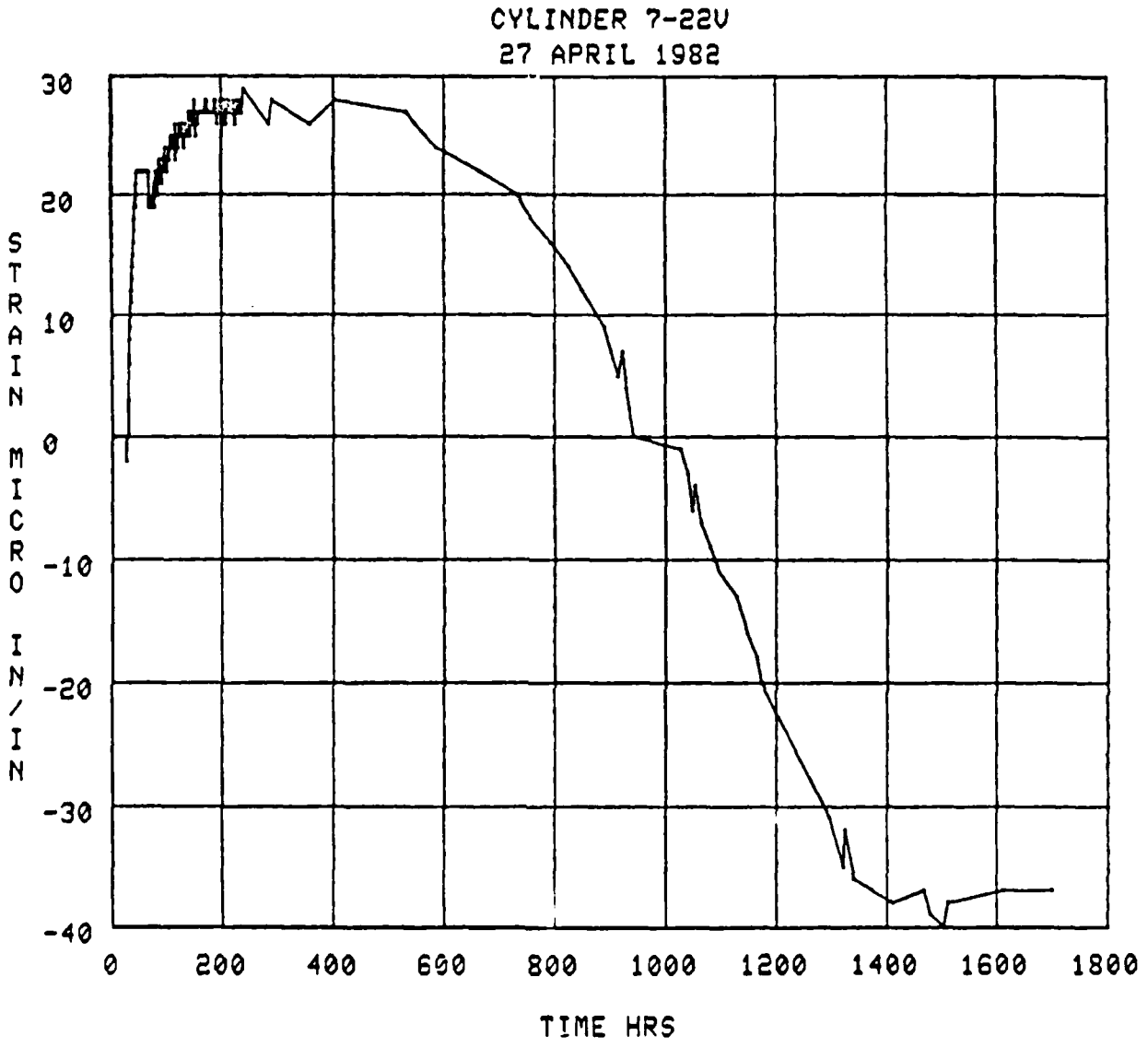
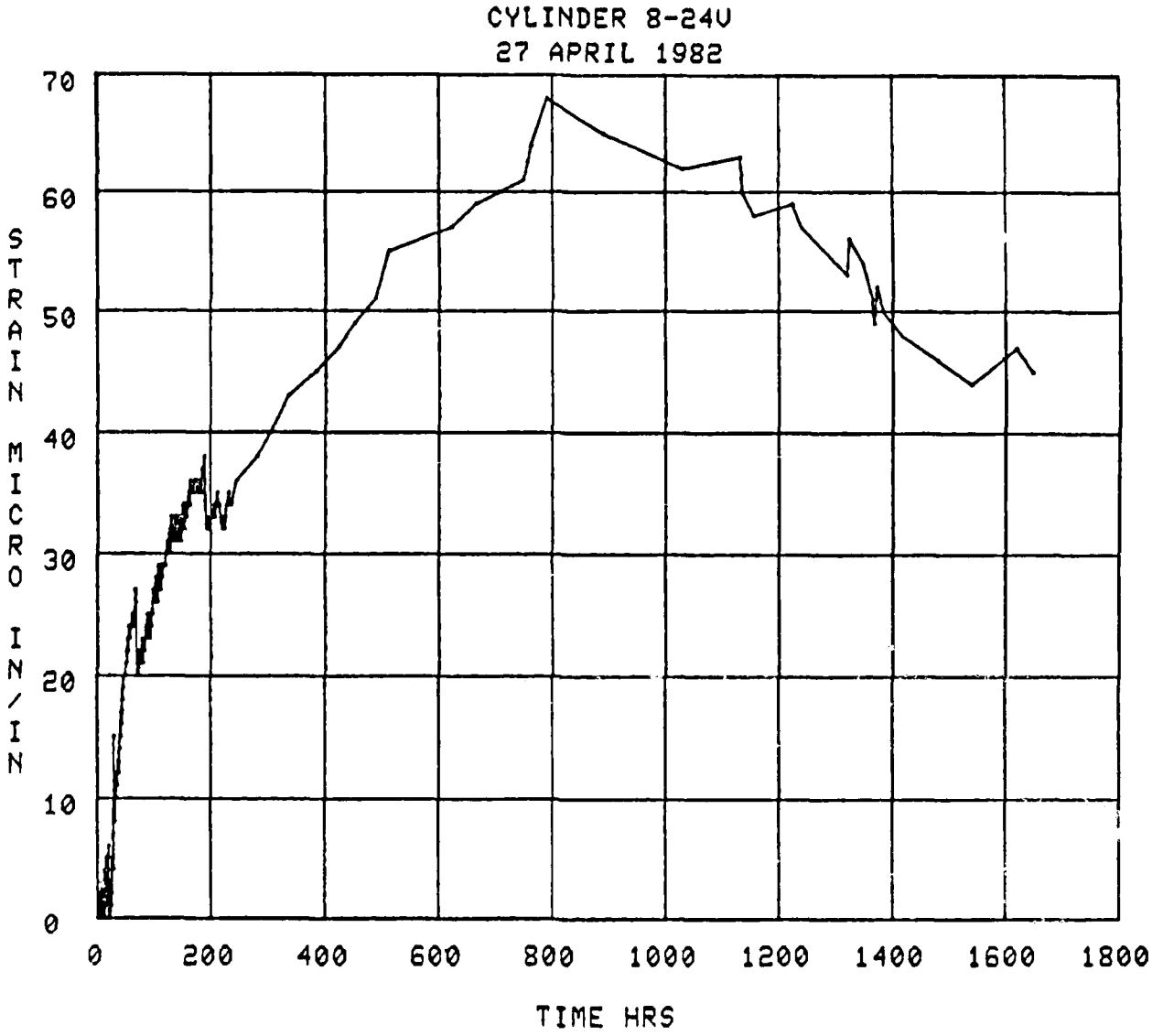
1200
1400
1600
1800
TIME HRS


CYLINDER 5-18V
27 APRIL 1982
STRAIN MICRO IN/IN
50
40
30
20
10
0
-10
-20
-30
-40
0
200
400
600
800
1000
1200
1400
1600
TIME HRS


CYLINDER 6-20V
27 APRIL 1982
STRAIN MICRO IN/IN
40
30
20
10
0
-10
-20
-30
-40
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 7-22V
27 APRIL 1982
STRAIN MICRO IN/IN
30
20
10
0
-10
-20
-30
-40
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 8-24U
27 APRIL 1982
STRAIN MICRO IN/IN
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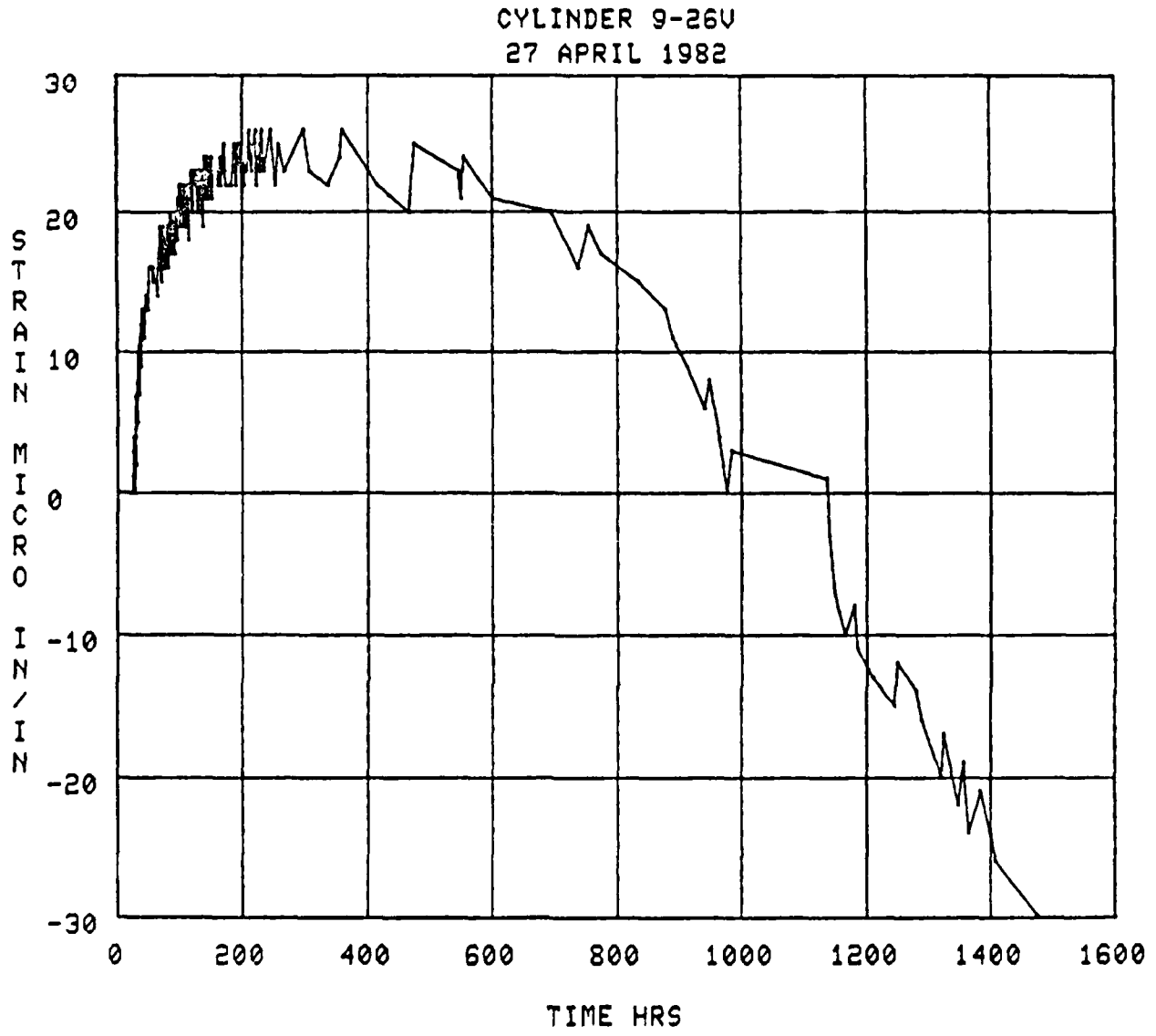
10
20
30
40
50
60
70
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 9-26V
27 APRIL 1982
STRAIN MICRO IN/IN
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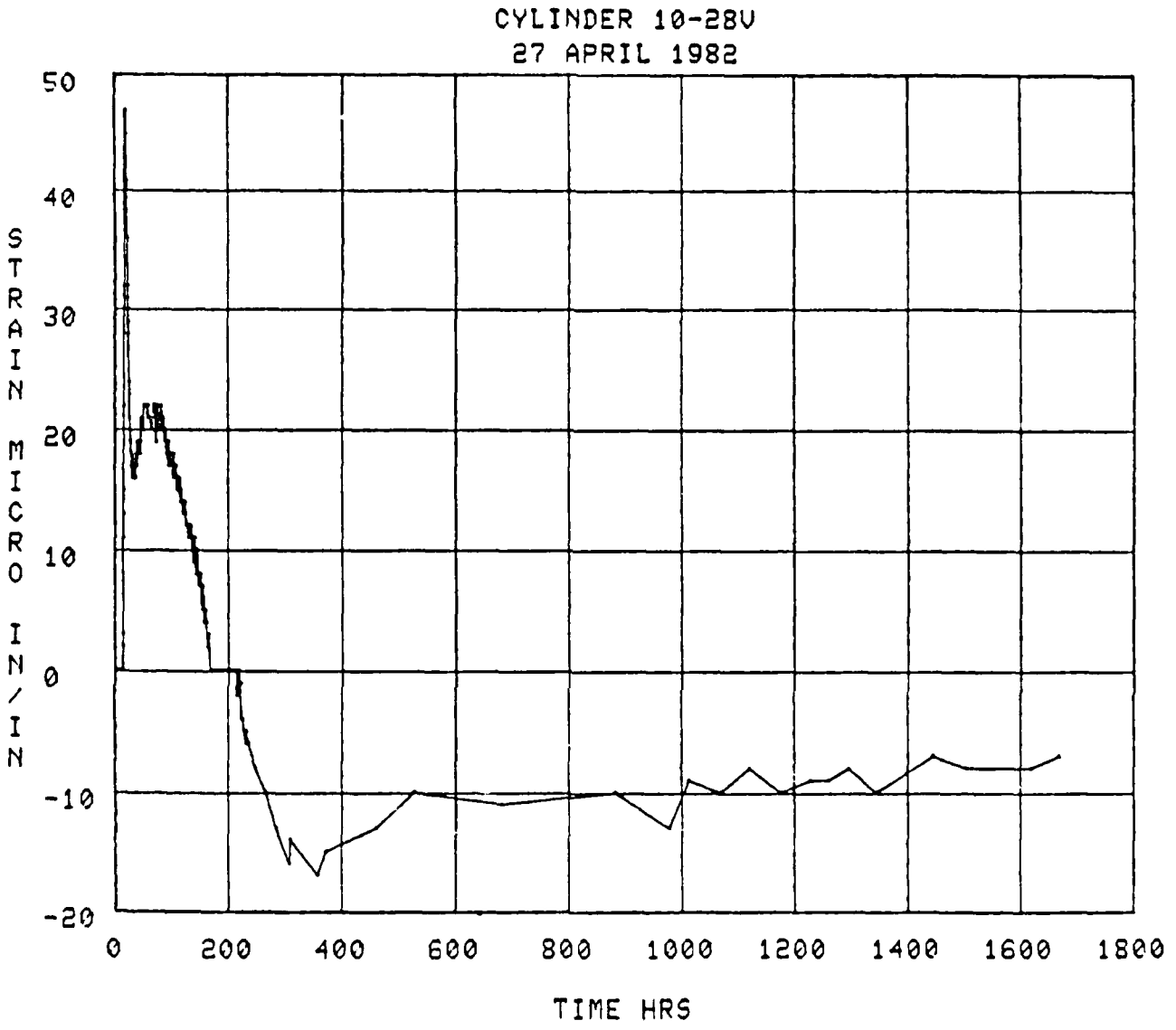
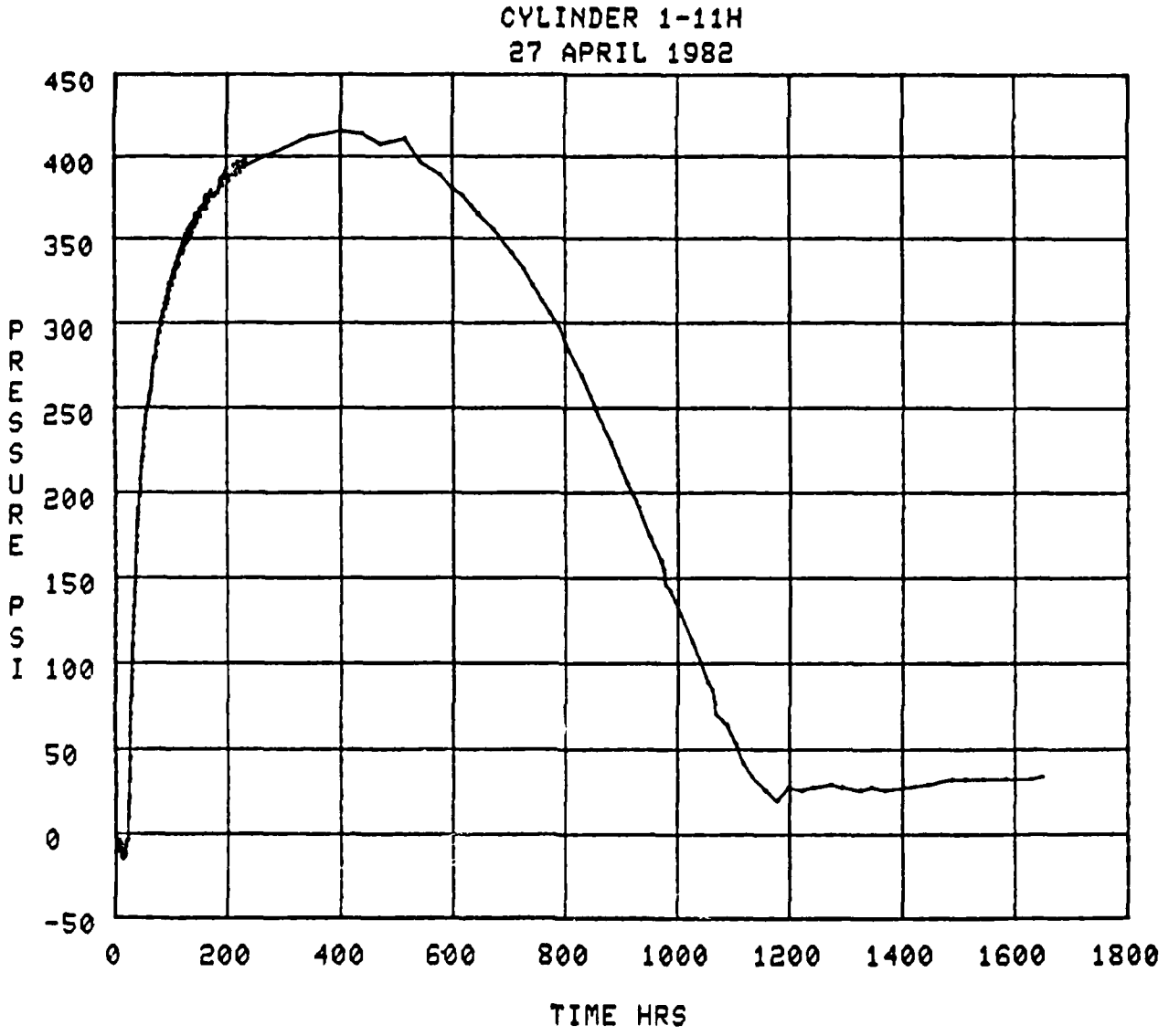
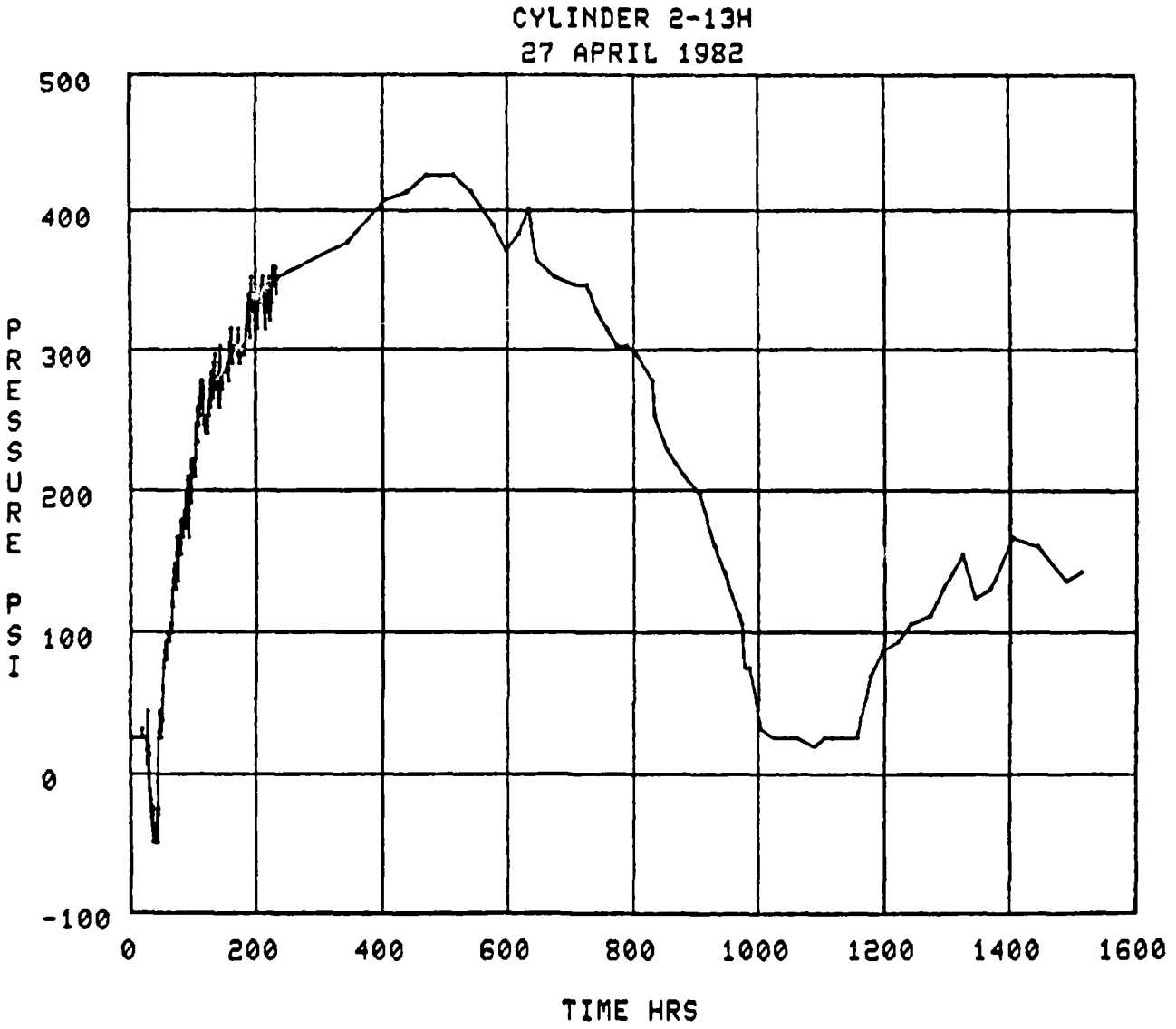
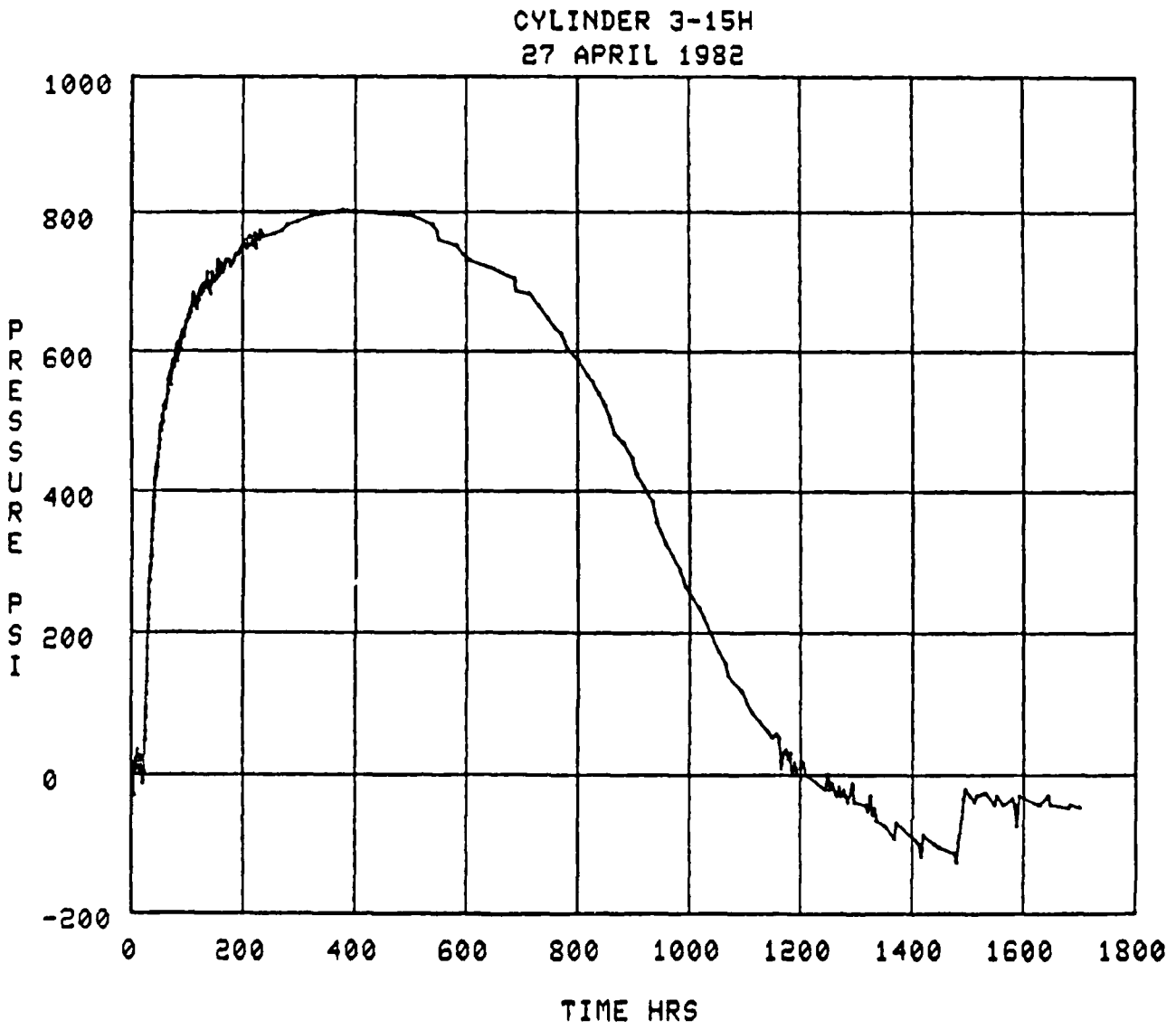
20
10
0
-10
-20
-30
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

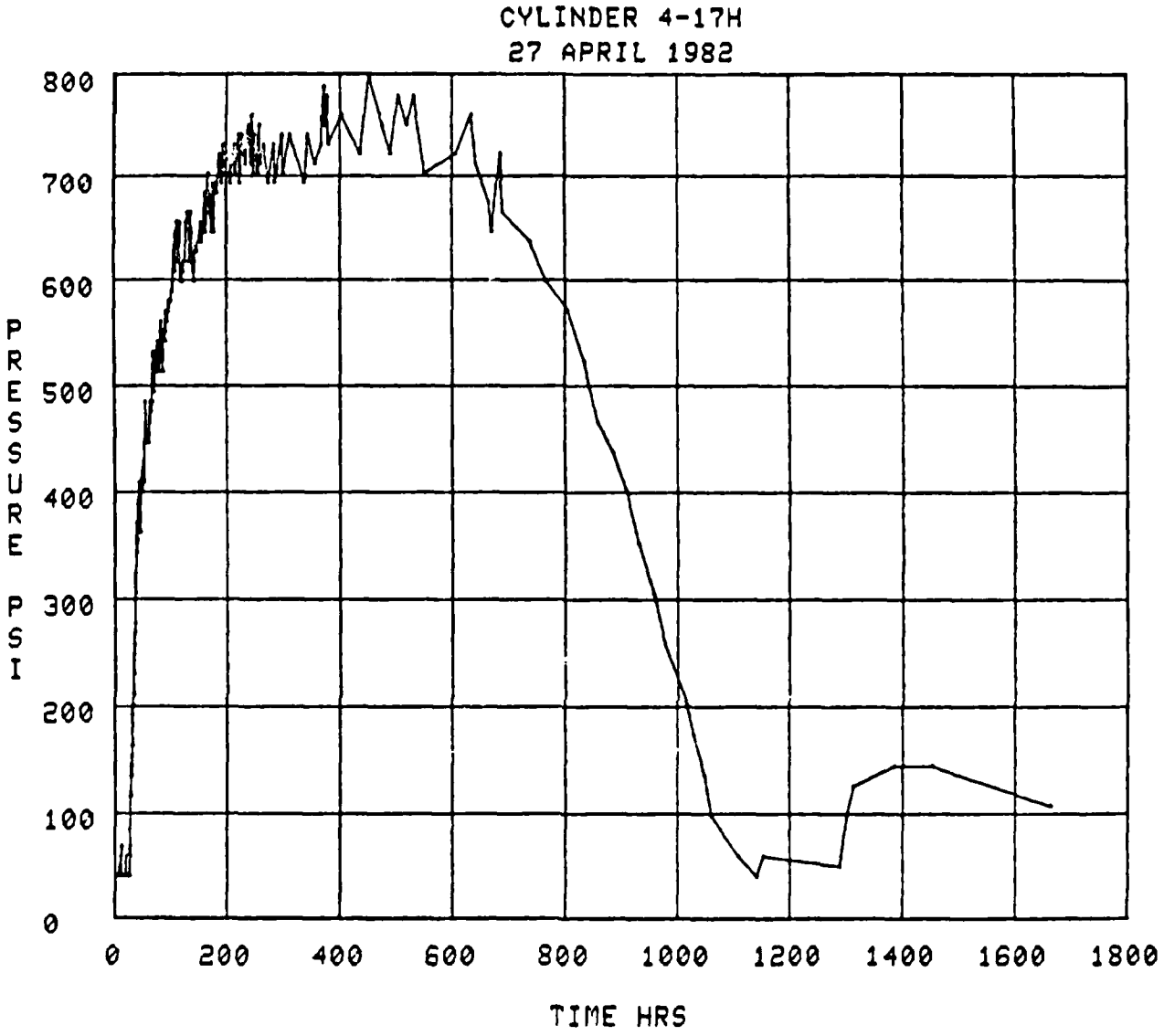

CYLINDER 10-28V
27 APRIL 1982
STRAIN MICRO IN/IN
50
40
30
20
10
0
-10
-20
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

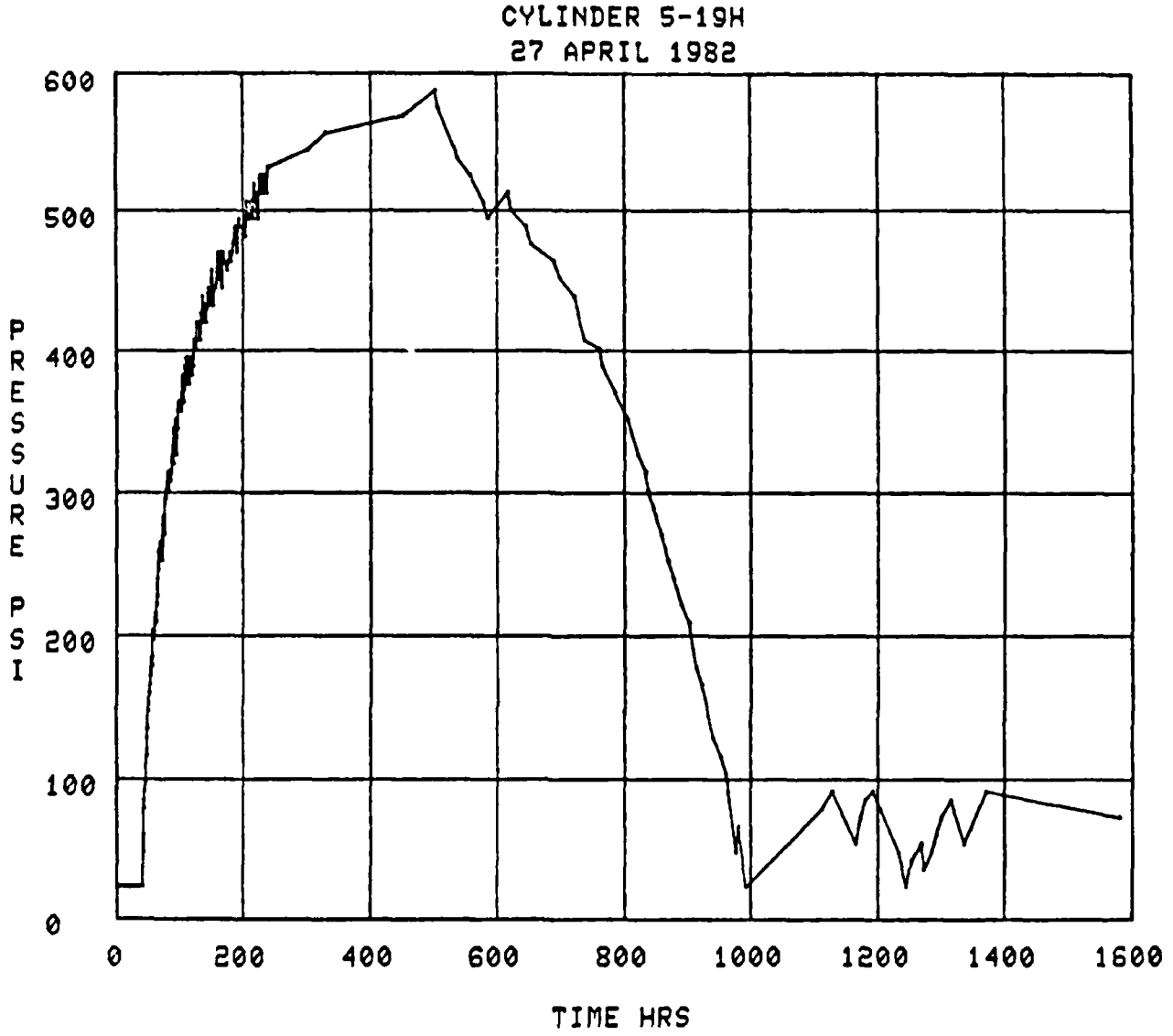
APPENDIX C: PRESSURE-TIME DATA FOR TANGENTIAL OR HOOP STRAINS

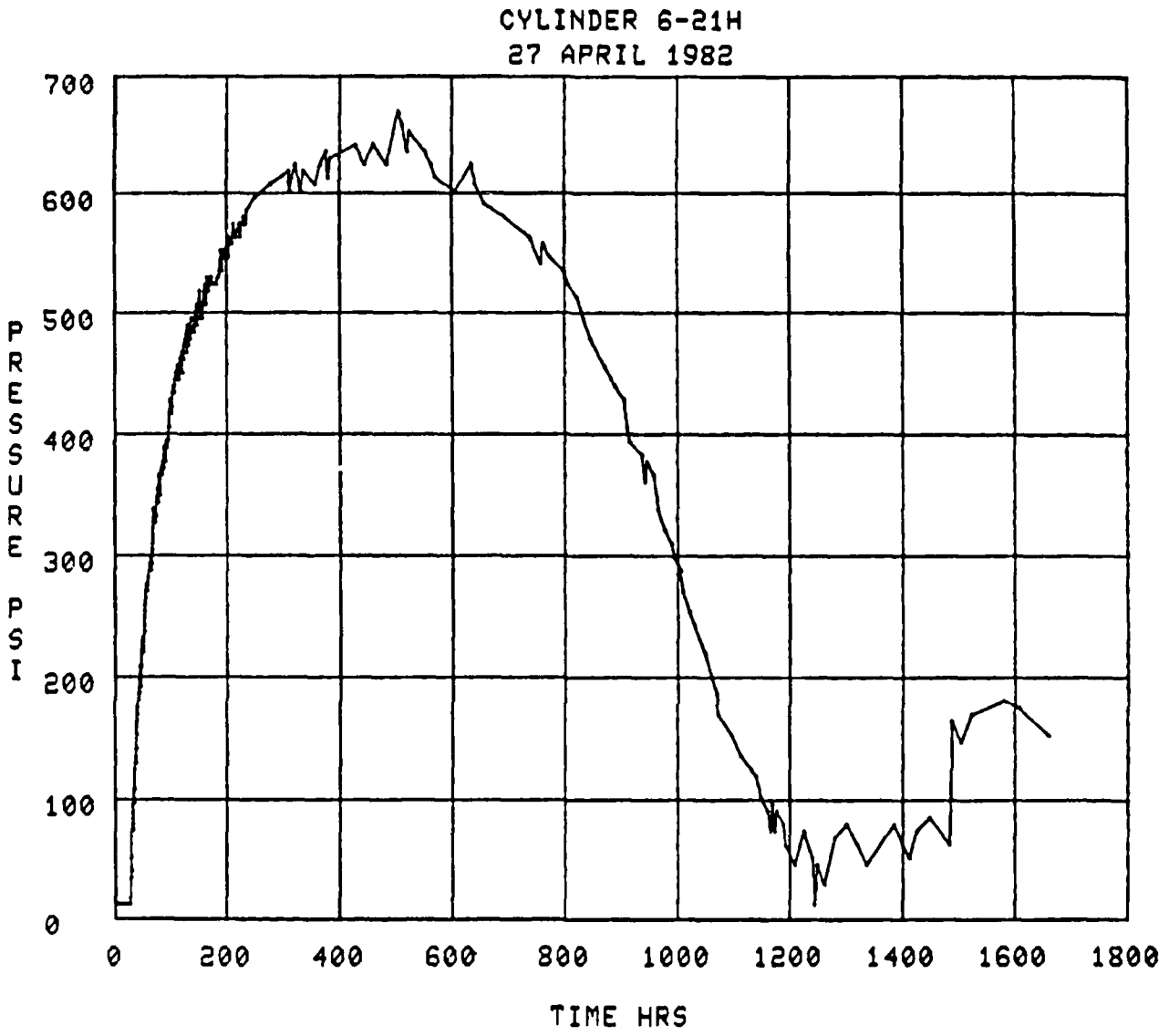

CYLINDER 1-11H
27 APRIL 1982
PRESSURE PSI
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

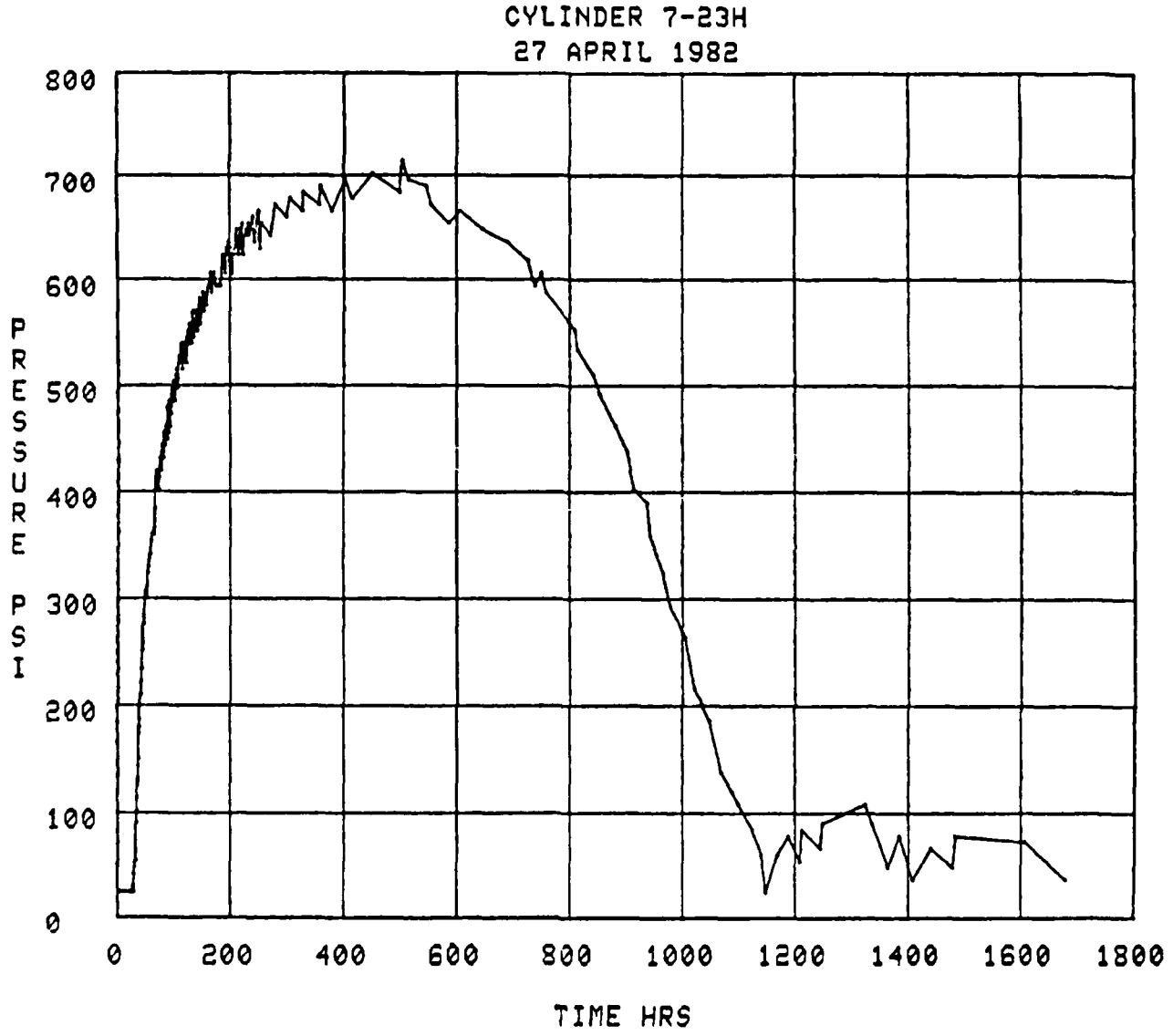

CYLINDER 2-13H
27 APRIL 1982
500
400
300
200
100
0
-100
PRESSURE PSI
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

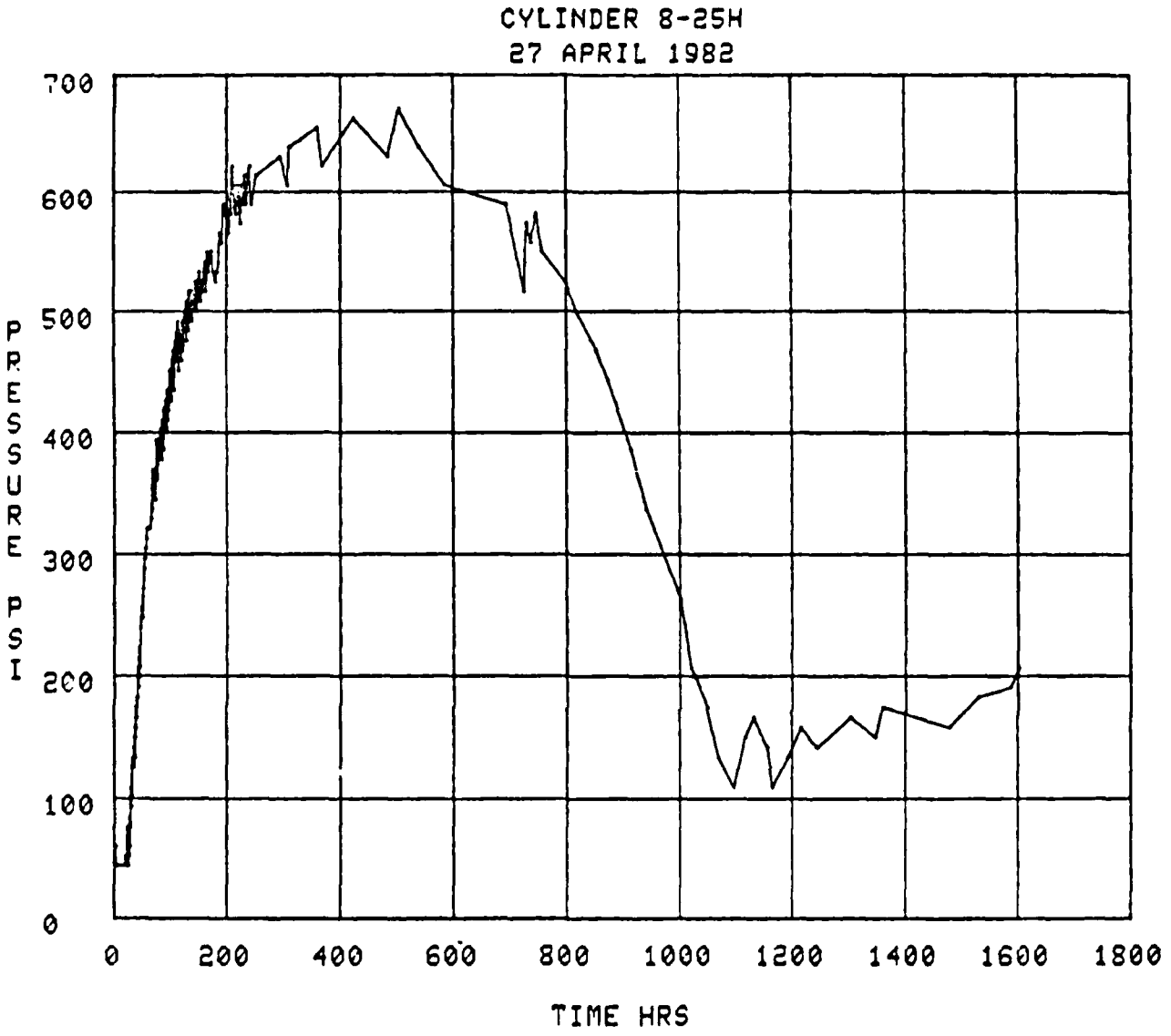

CYLINDER 3-15H
27 APRIL 1982
1000
800
600
400
200
0
-200
PRESSURE PSI
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

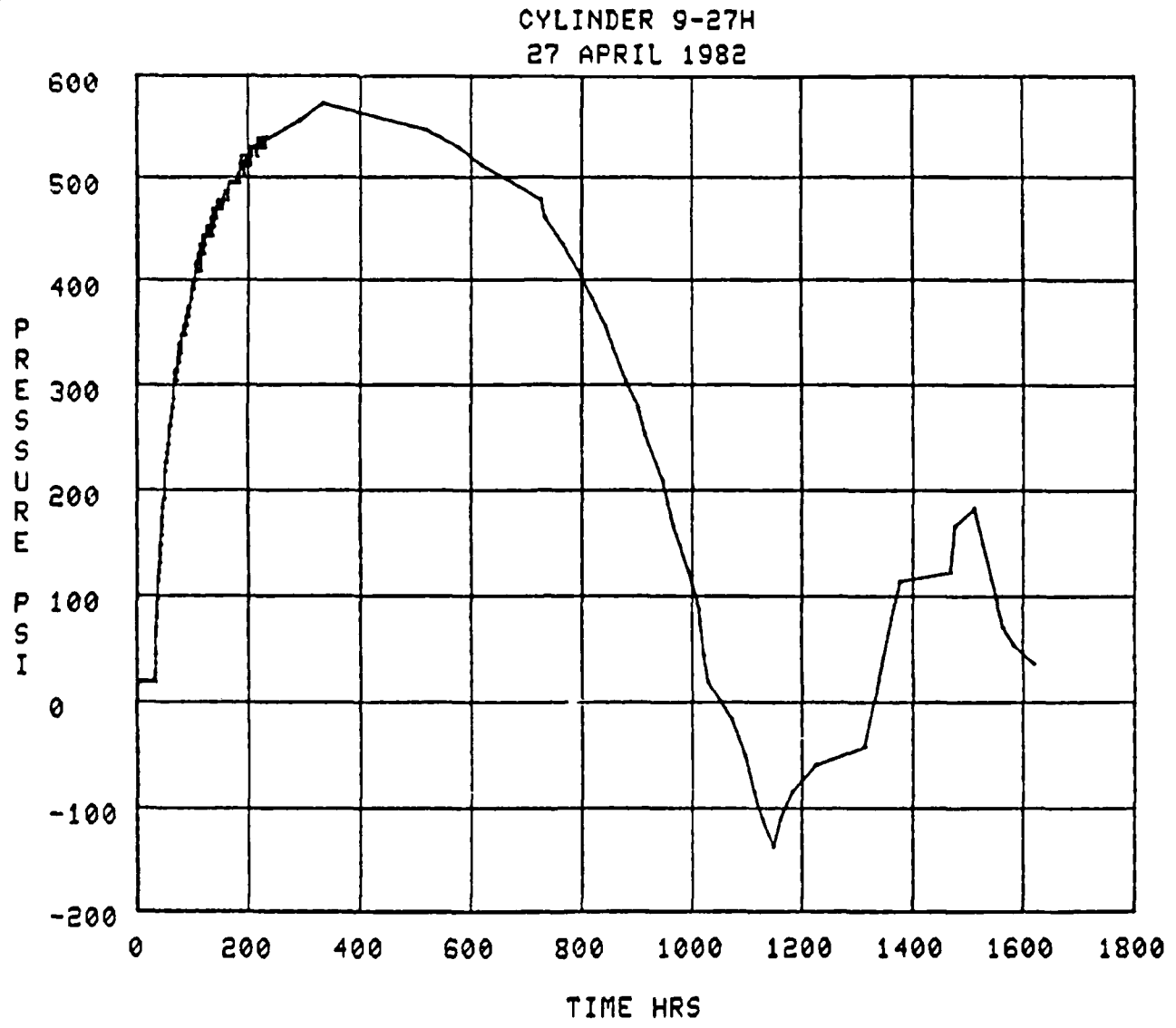

CYLINDER 4-17H
27 APRIL 1982
PRESSURE PSI
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

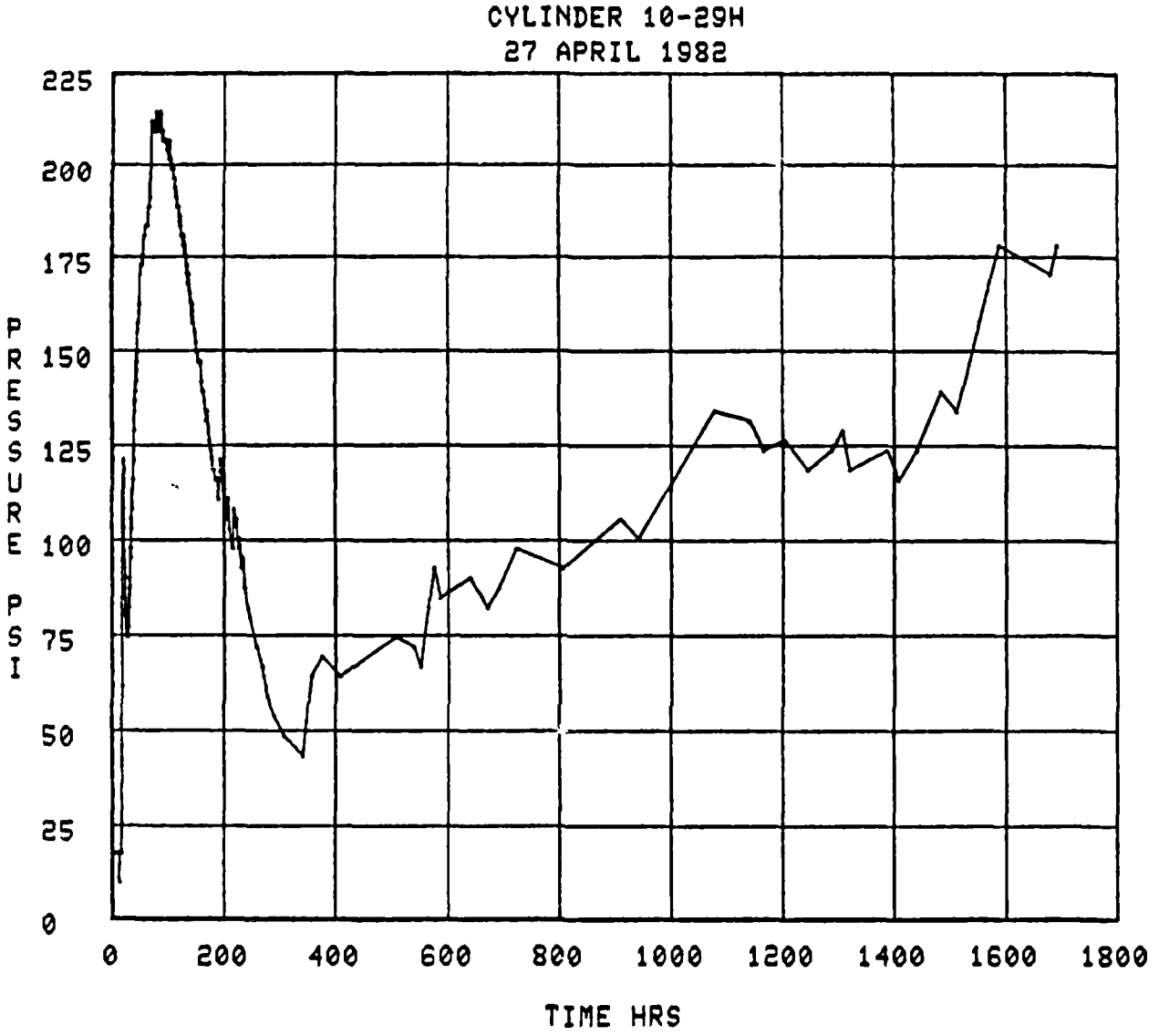

CYLINDER 5-19H
27 APRIL 1982
PRESSURE PSI
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
TIME HRS

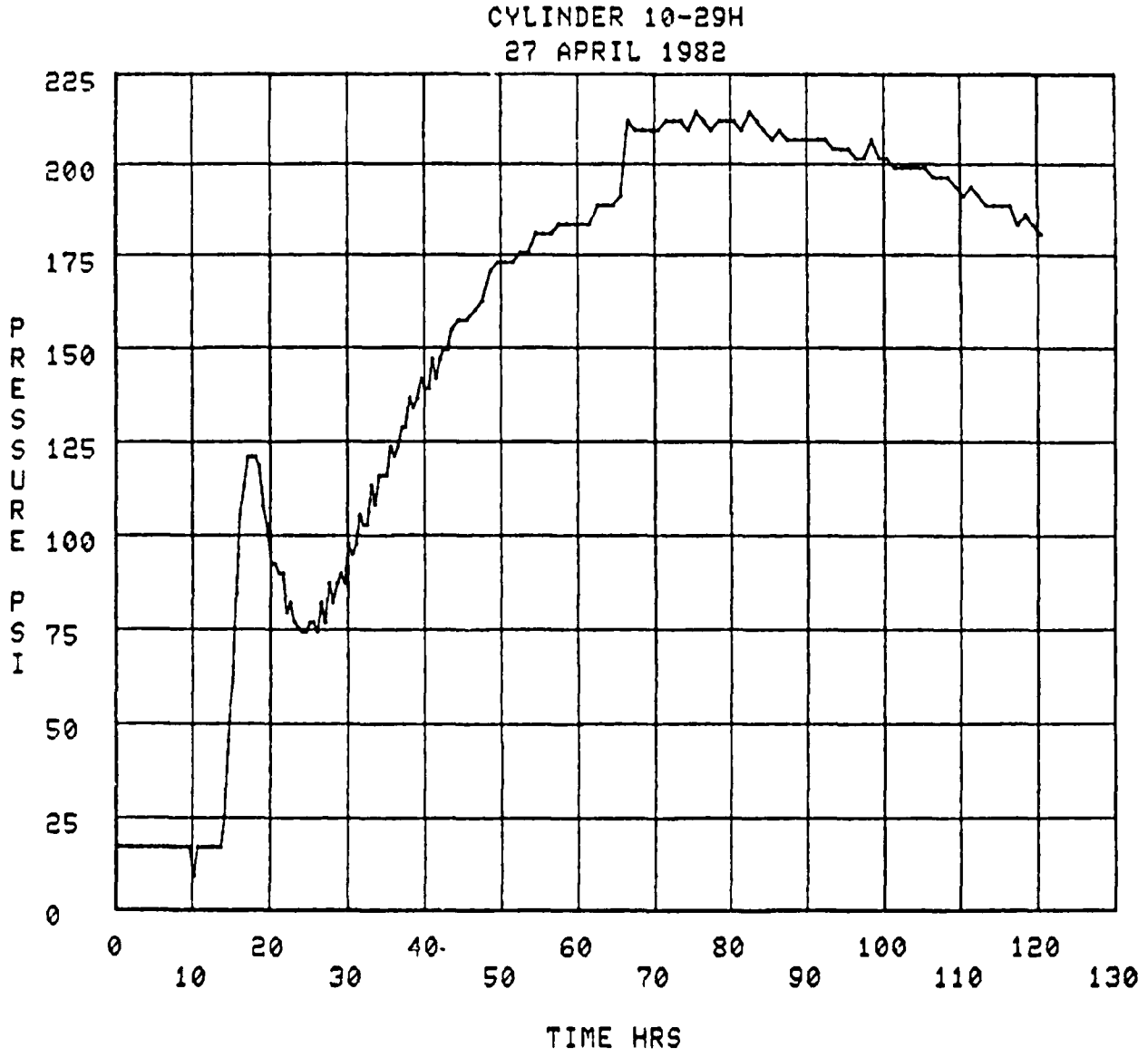

CYLINDER 6-21H
27 APRIL 1982
PRESSURE PSI
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 7-23H
27 APRIL 1982
PRESSURE PSI
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

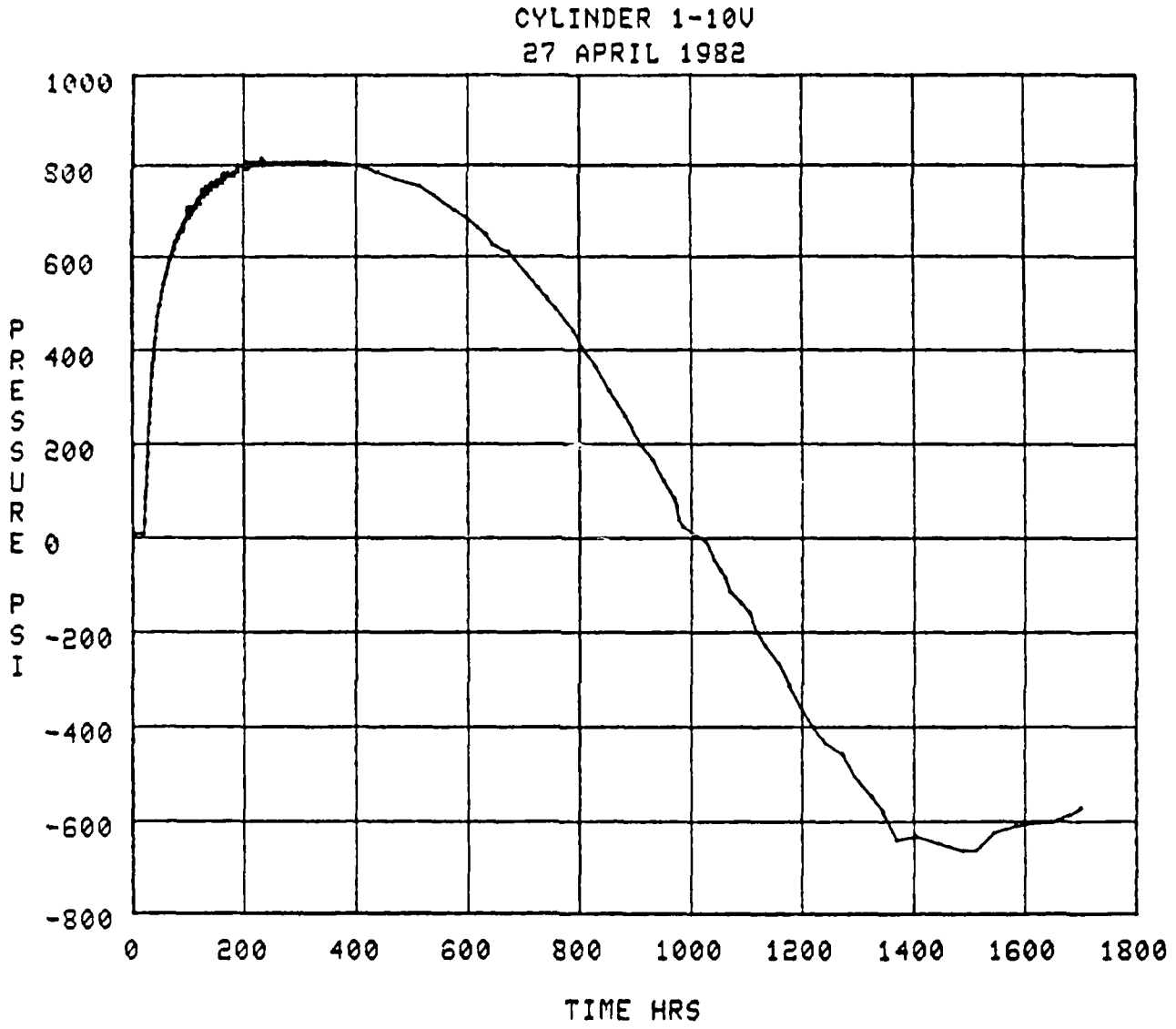

CYLINDER 8-25H
27 APRIL 1982
700
600
500
400
300
200
100
0
PRESSURE PSI
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 9-27H
27 APRIL 1982
600
500
400
300
200
100
0
-100
-200
PRESSURE PSI
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 10-29H
27 APRIL 1982
PRESSURE PSI
225
200
175
150
125
100
75
50
25
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 10-29H
27 APRIL 1982
PRESSURE PSI
225
200
175
150
125
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
TIME HRS

APPENDIX D: PRESSURES FOR LONGITUDINAL STRAINS


CYLINDER 1-10V
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PRESSURE PSI
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400
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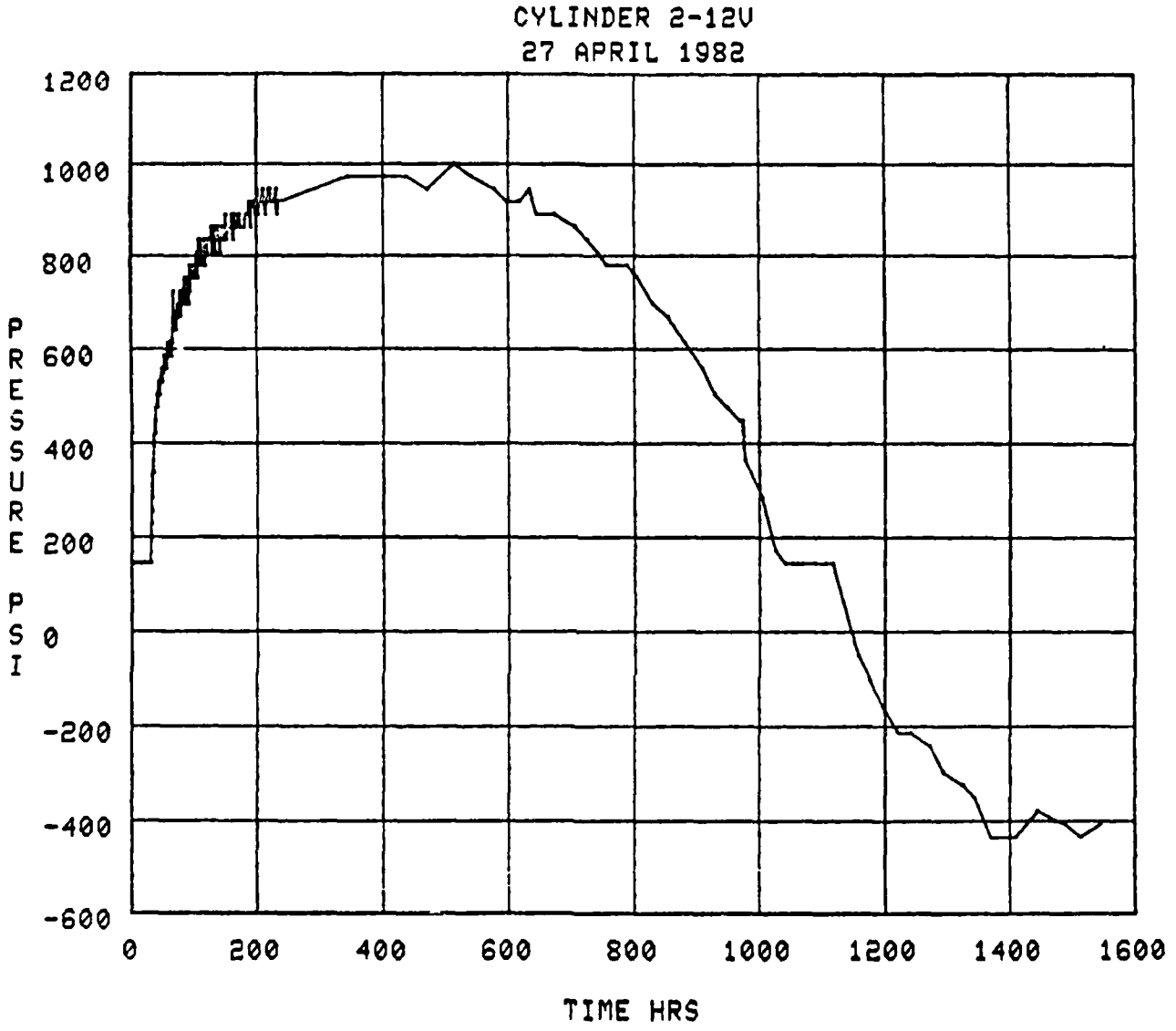
1400
1600
1800
TIME HRS


CYLINDER 2-12V
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PRESSURE PSI
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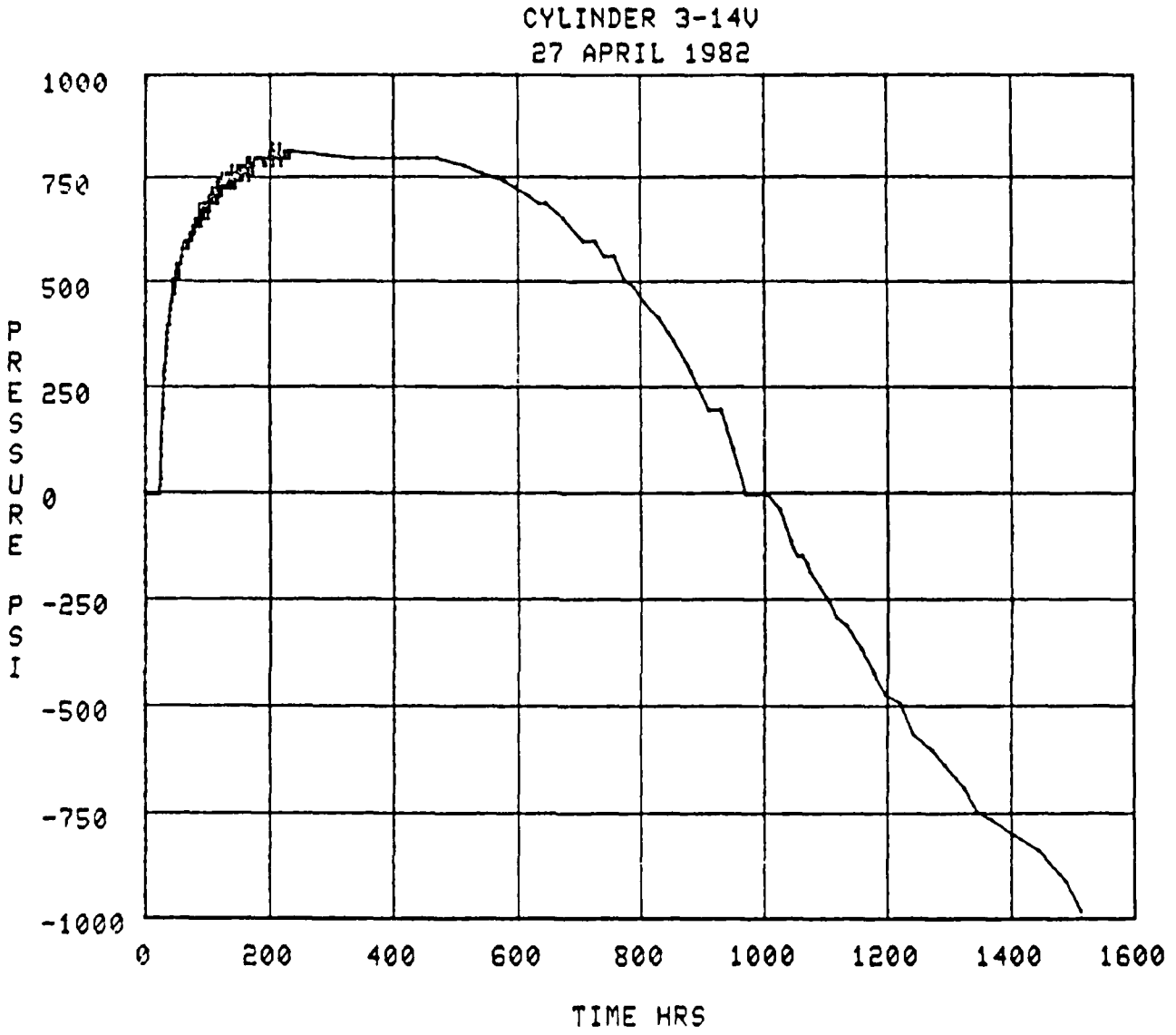
TIME HRS


CYLINDER 3-14V
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PRESSURE PSI
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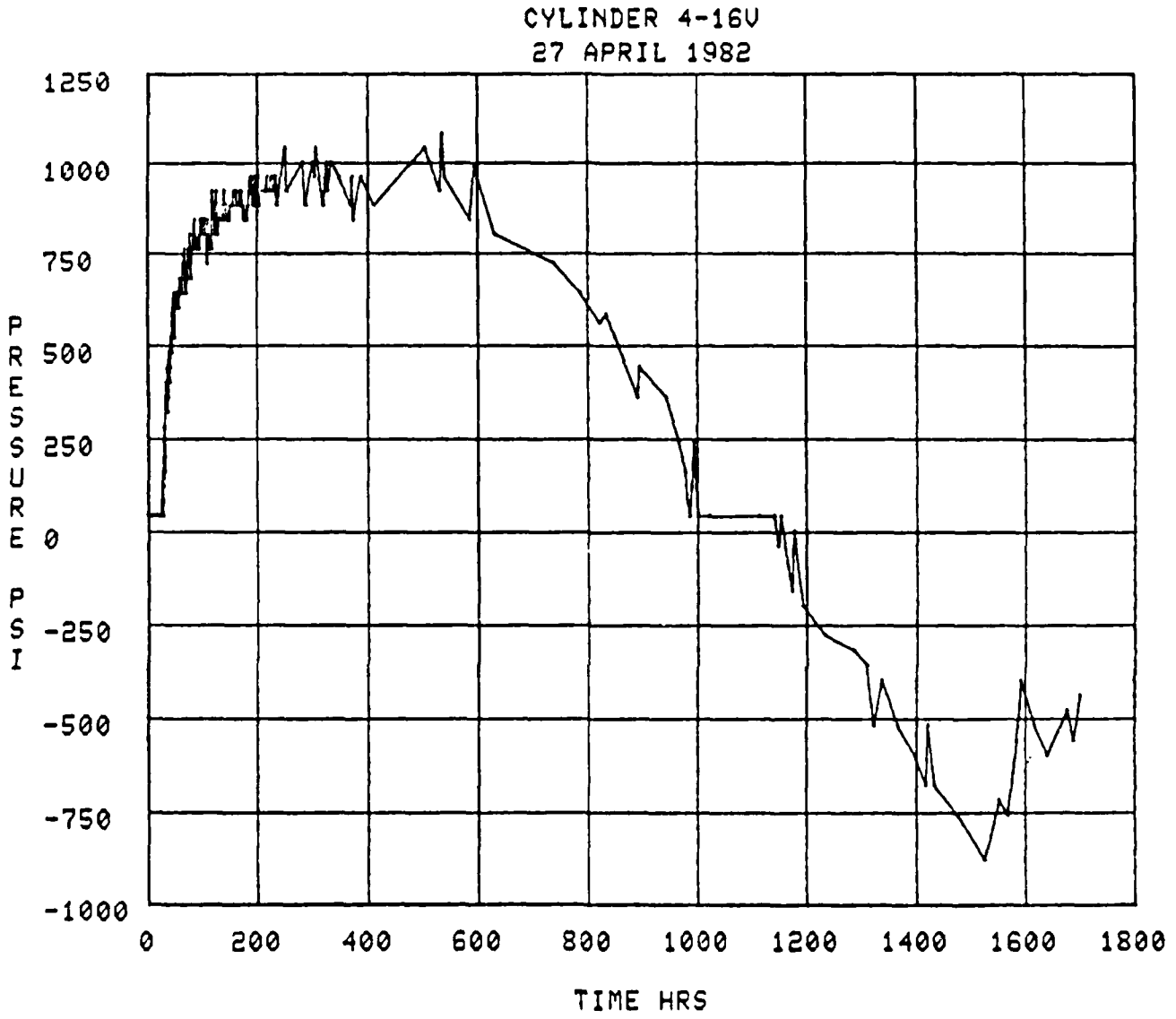
1400
1600
TIME HRS


CYLINDER 4-16V
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PRESSURE PSI
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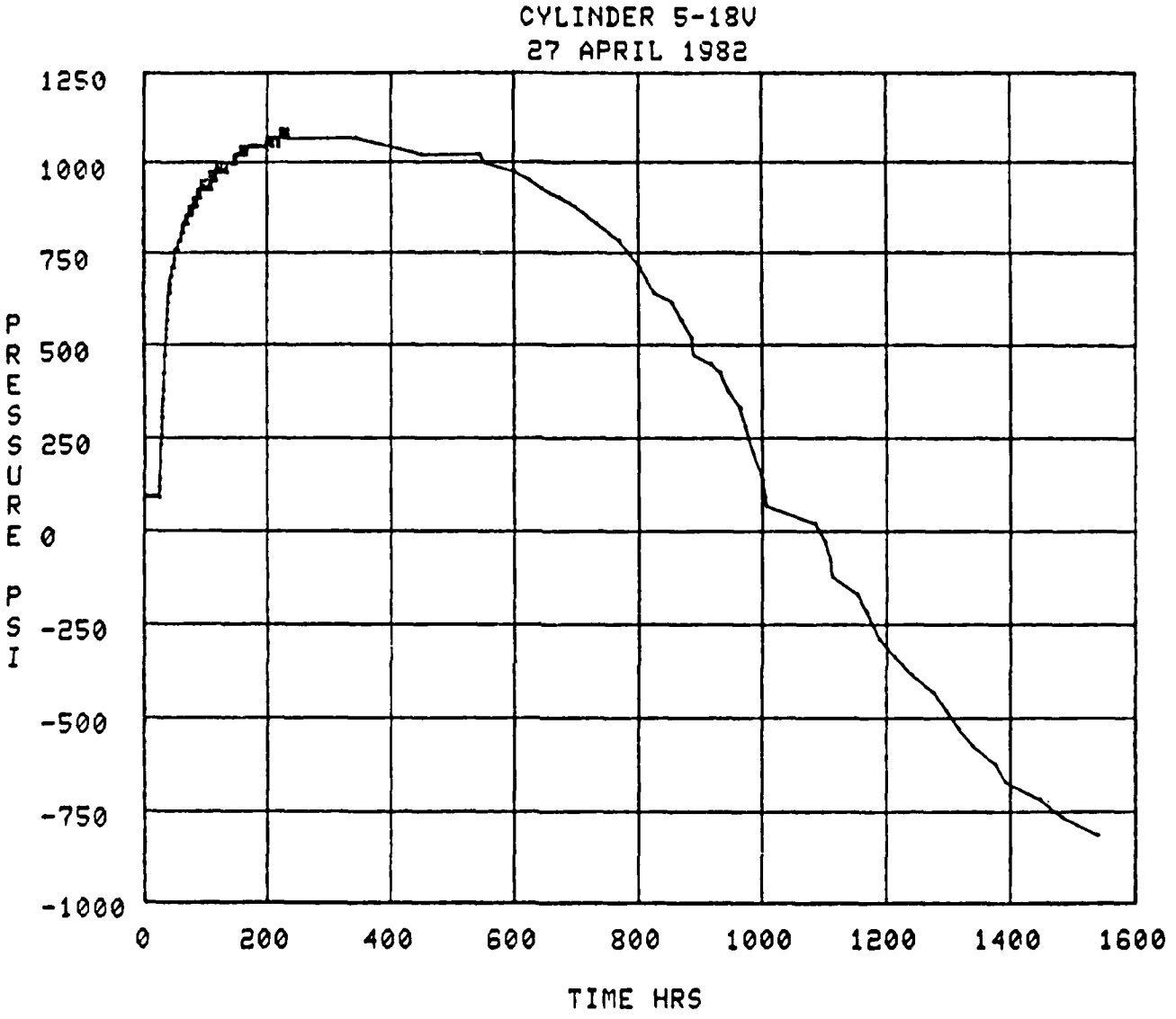
1400
1600
1800
TIME HRS


CYLINDER 5-18V
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PRESSURE PSI
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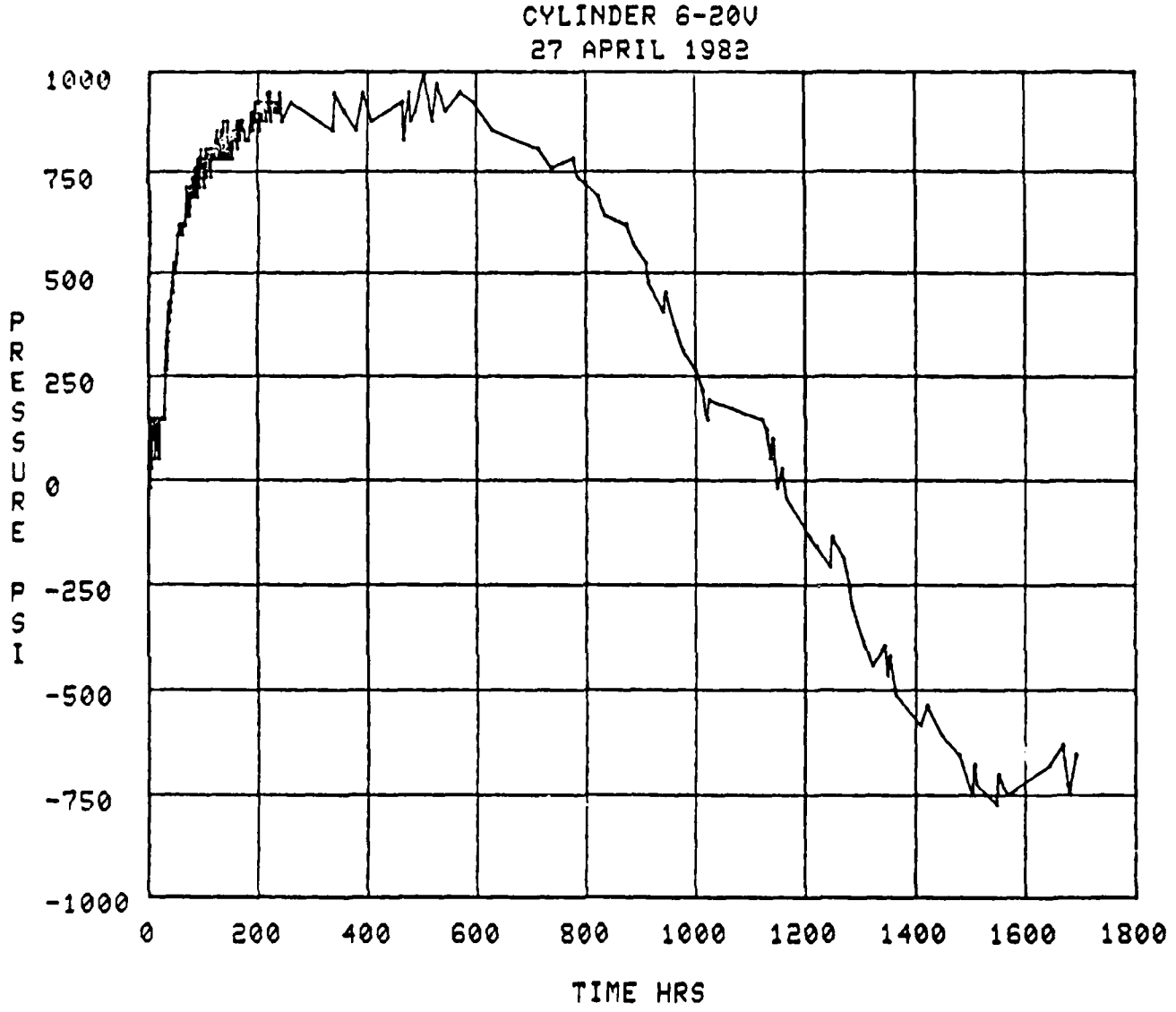
1400
1600
TIME HRS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PRESSURE PSI
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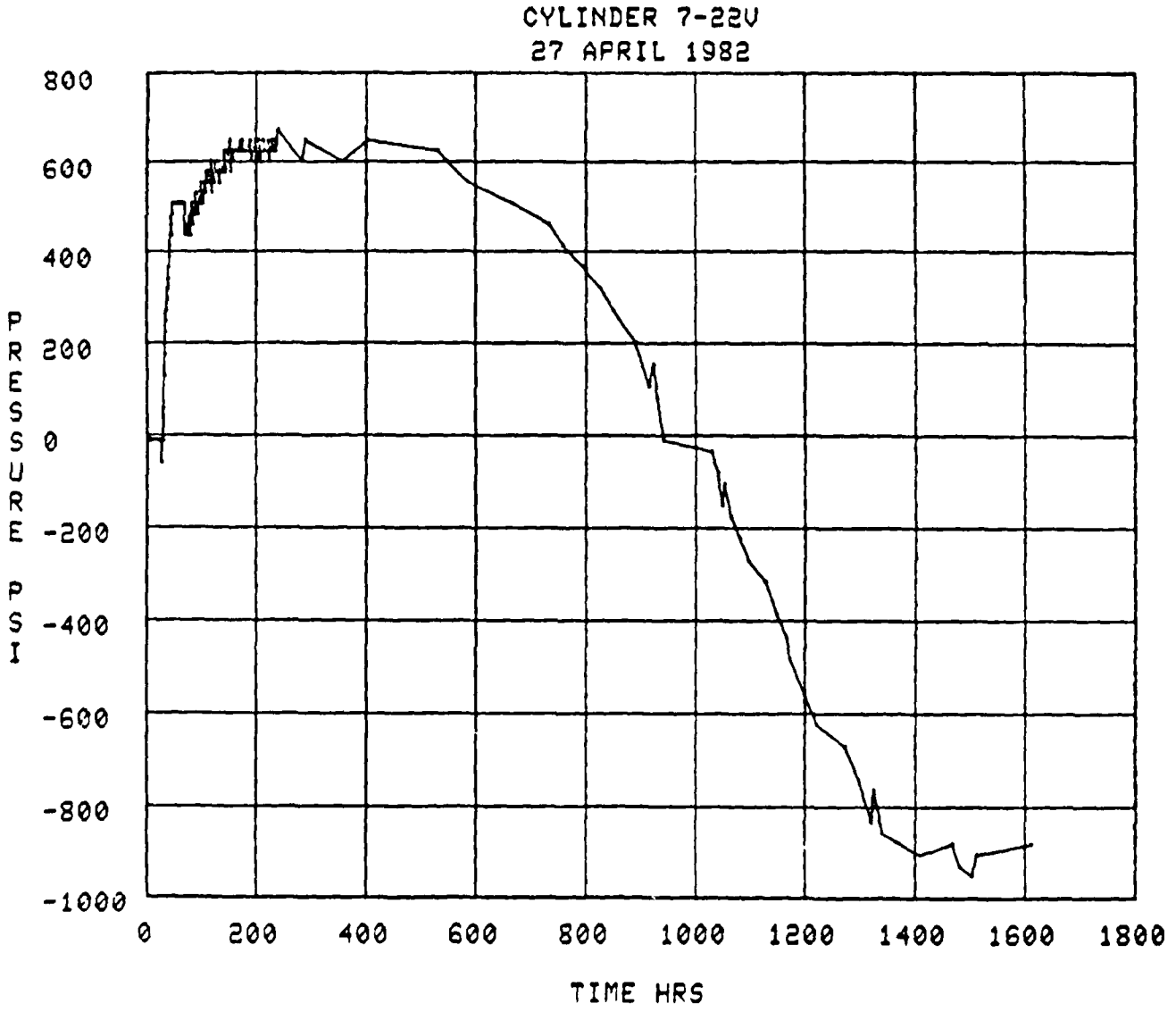
1200
1400
1600
1800
TIME HRS


CYLINDER 7-22V
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400
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PRESSURE PSI
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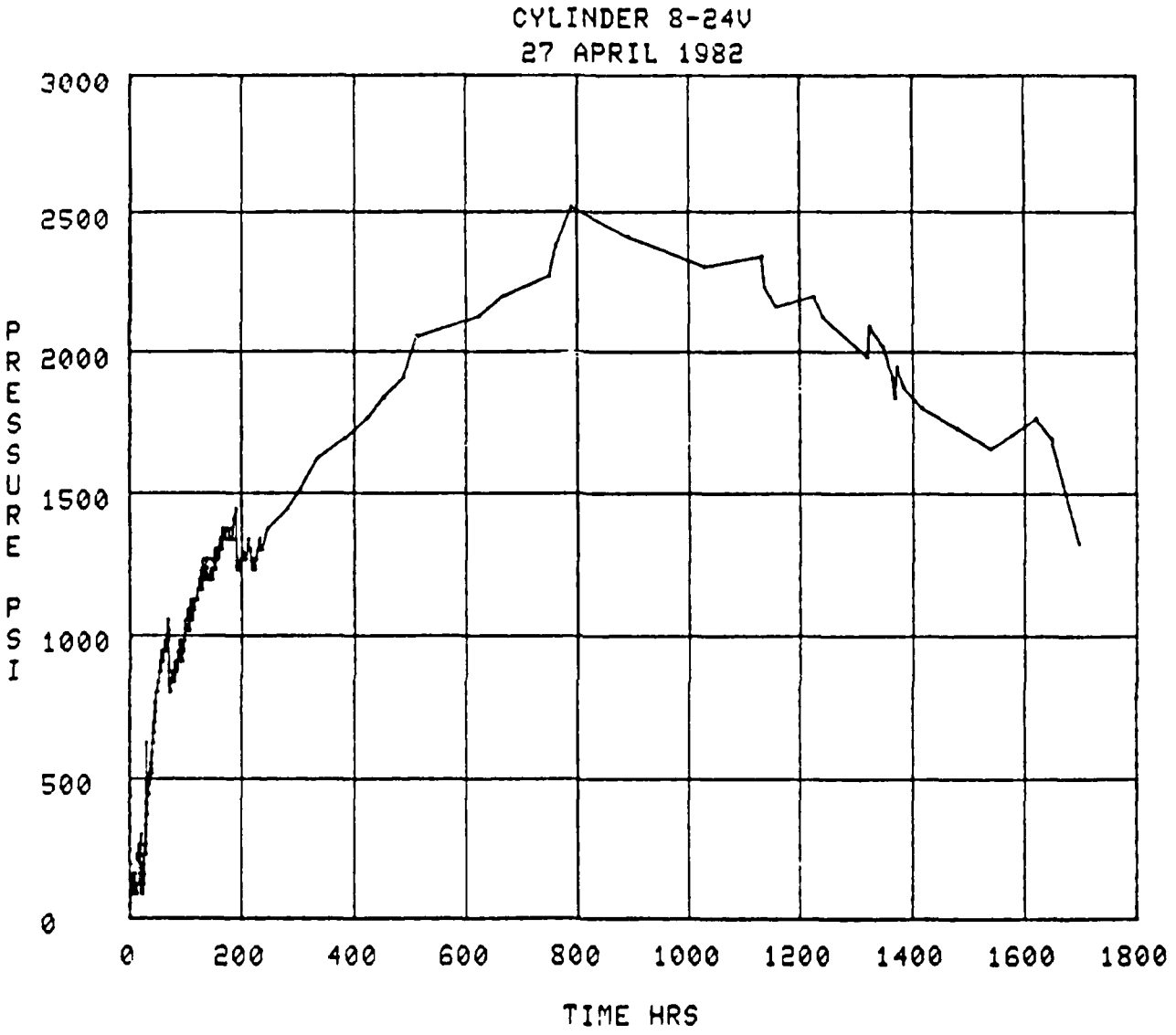
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 8-24V
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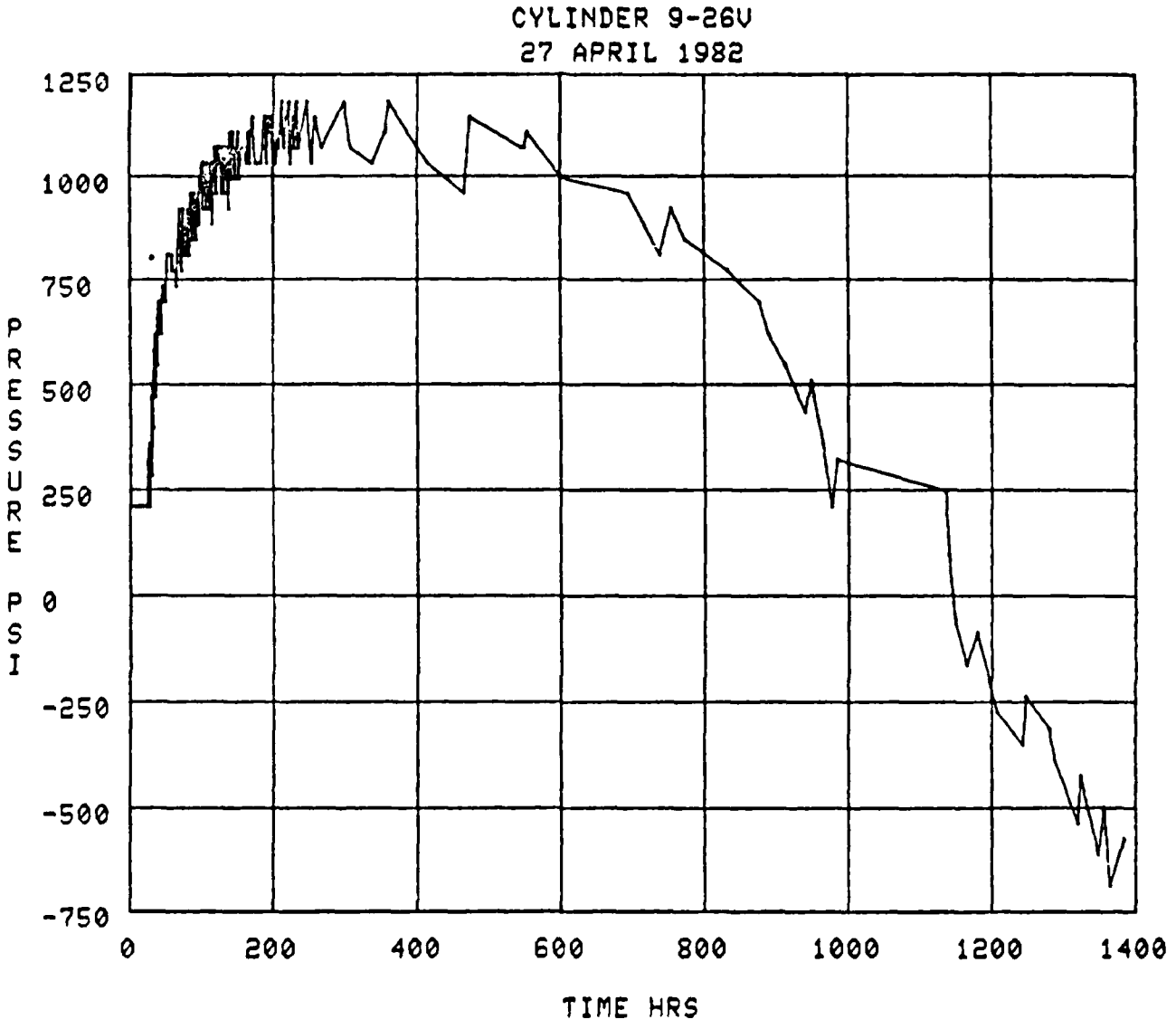
1400
1600
1800
TIME HRS


CYLINDER 9-26V
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PRESSURE PSI
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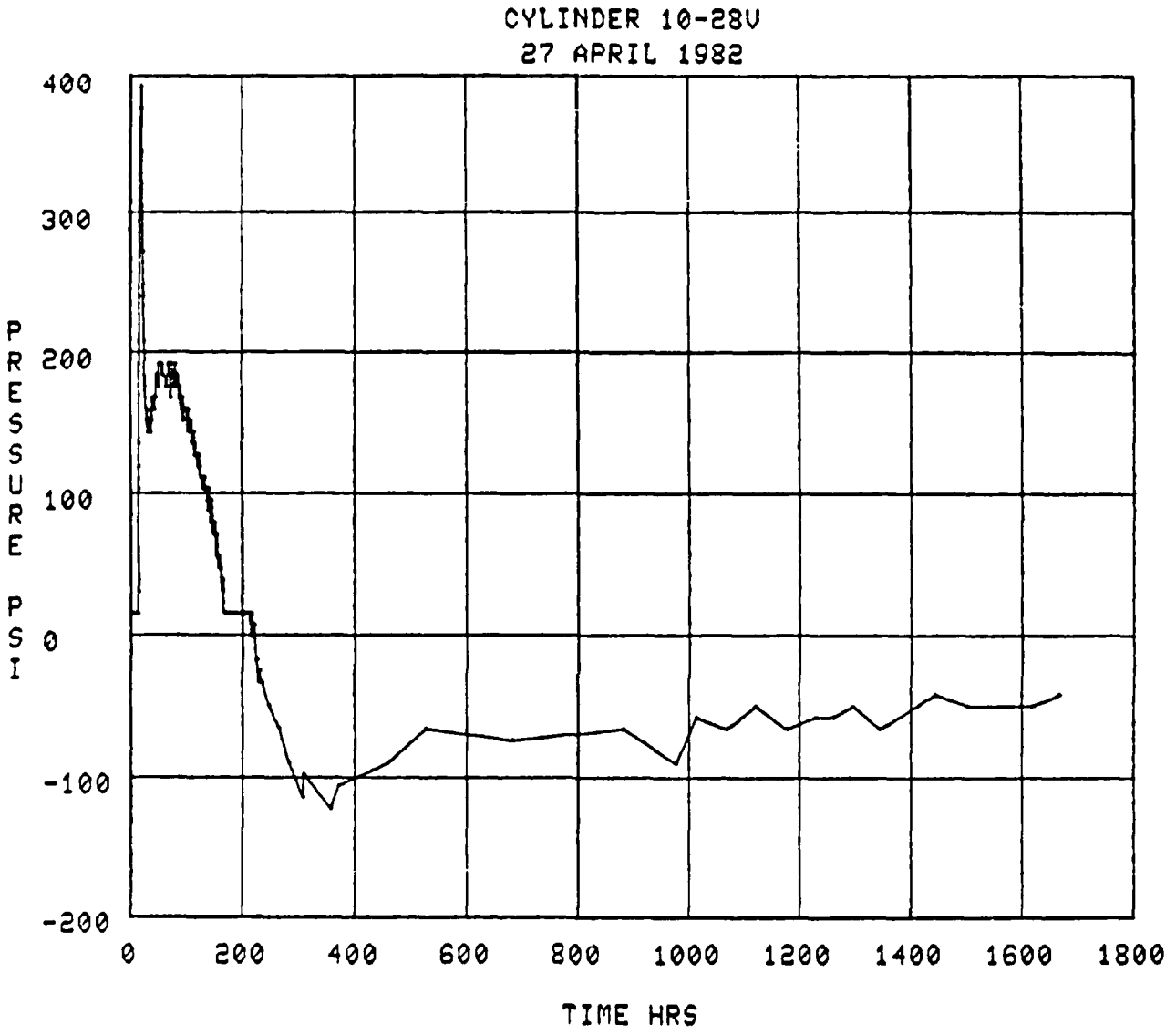
1400
TIME HRS


CYLINDER 10-28V
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400
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200
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-100
-200
PRESSURE PSI
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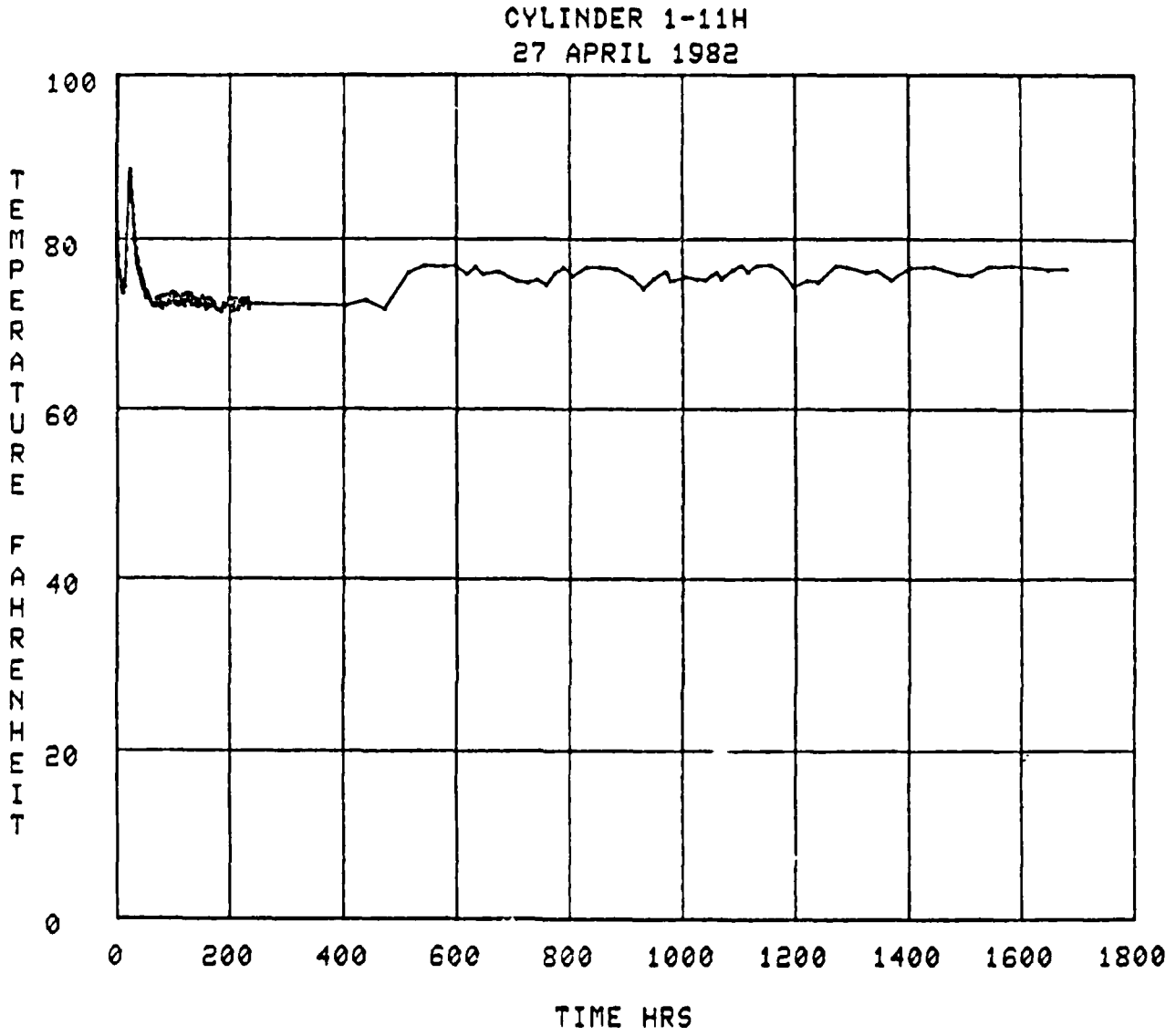
400
600
800
1000
1200
1400
1600
1800
TIME HRS

APPENDIX E: TEMPERATURE-VERSUS-TIME DATA


CYLINDER 1-11H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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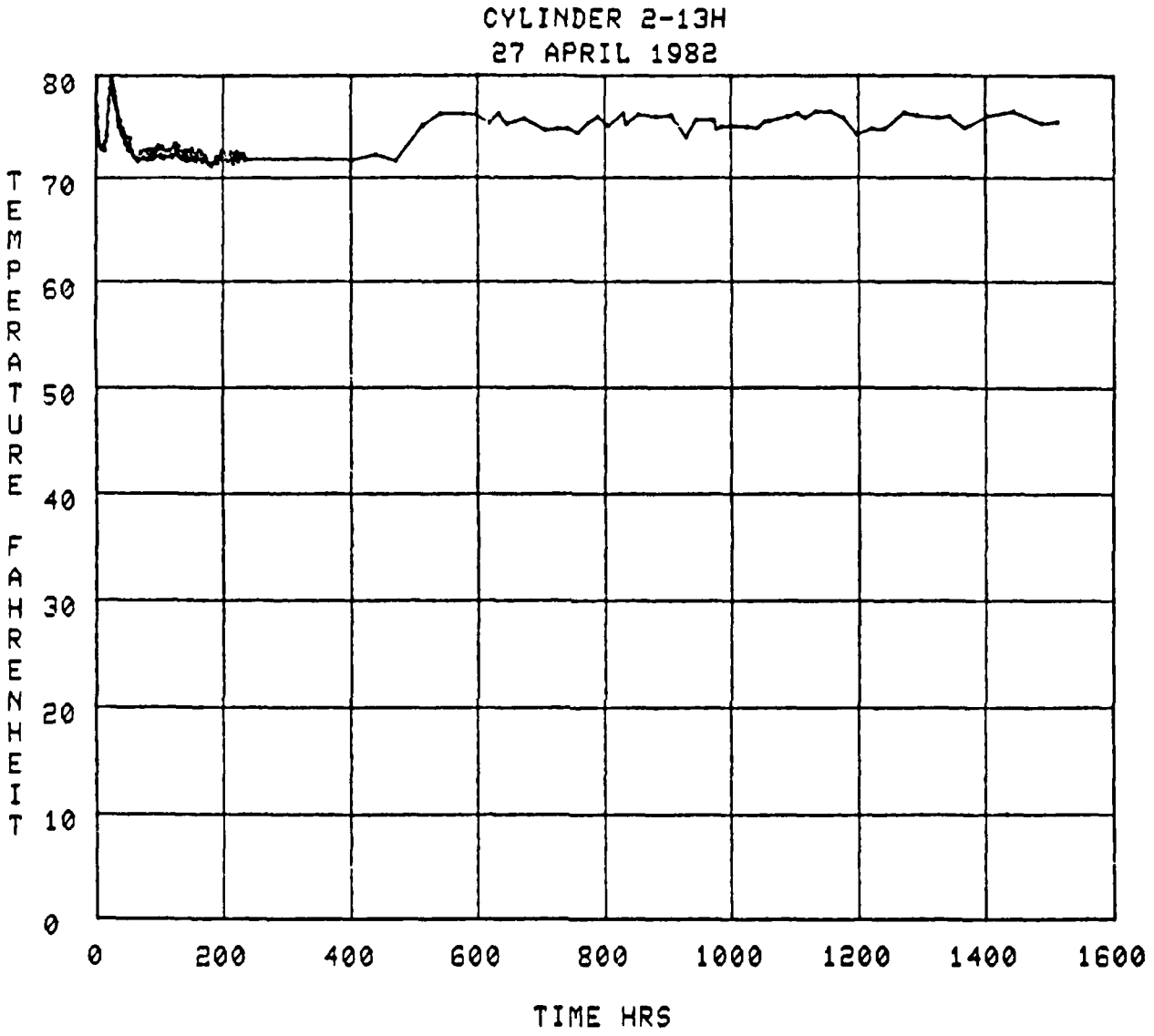
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 2-13H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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40
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20
10
0
0
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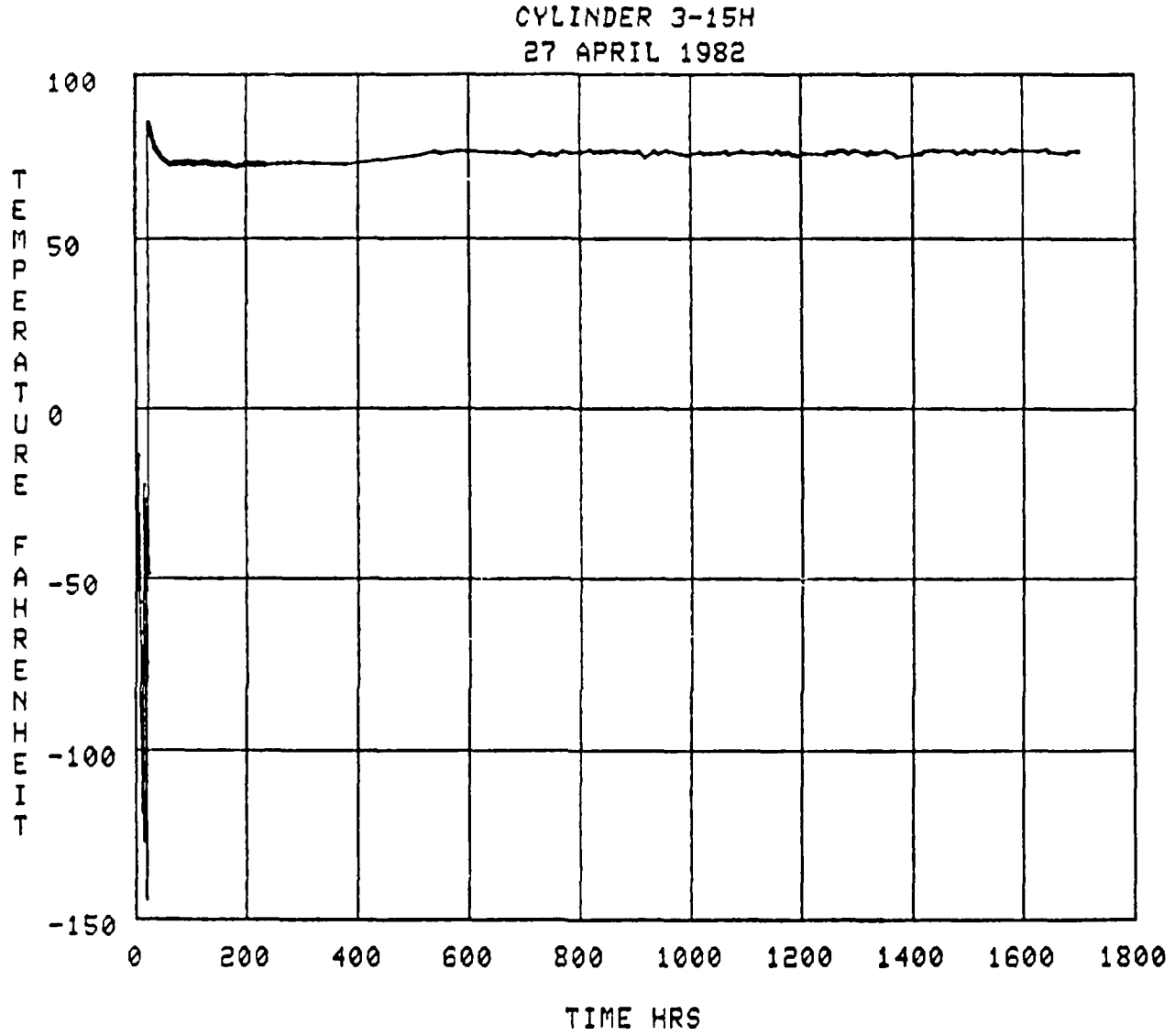
400
600
800
1000
1200
1400
1600
TIME HRS


CYLINDER 3-15H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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0
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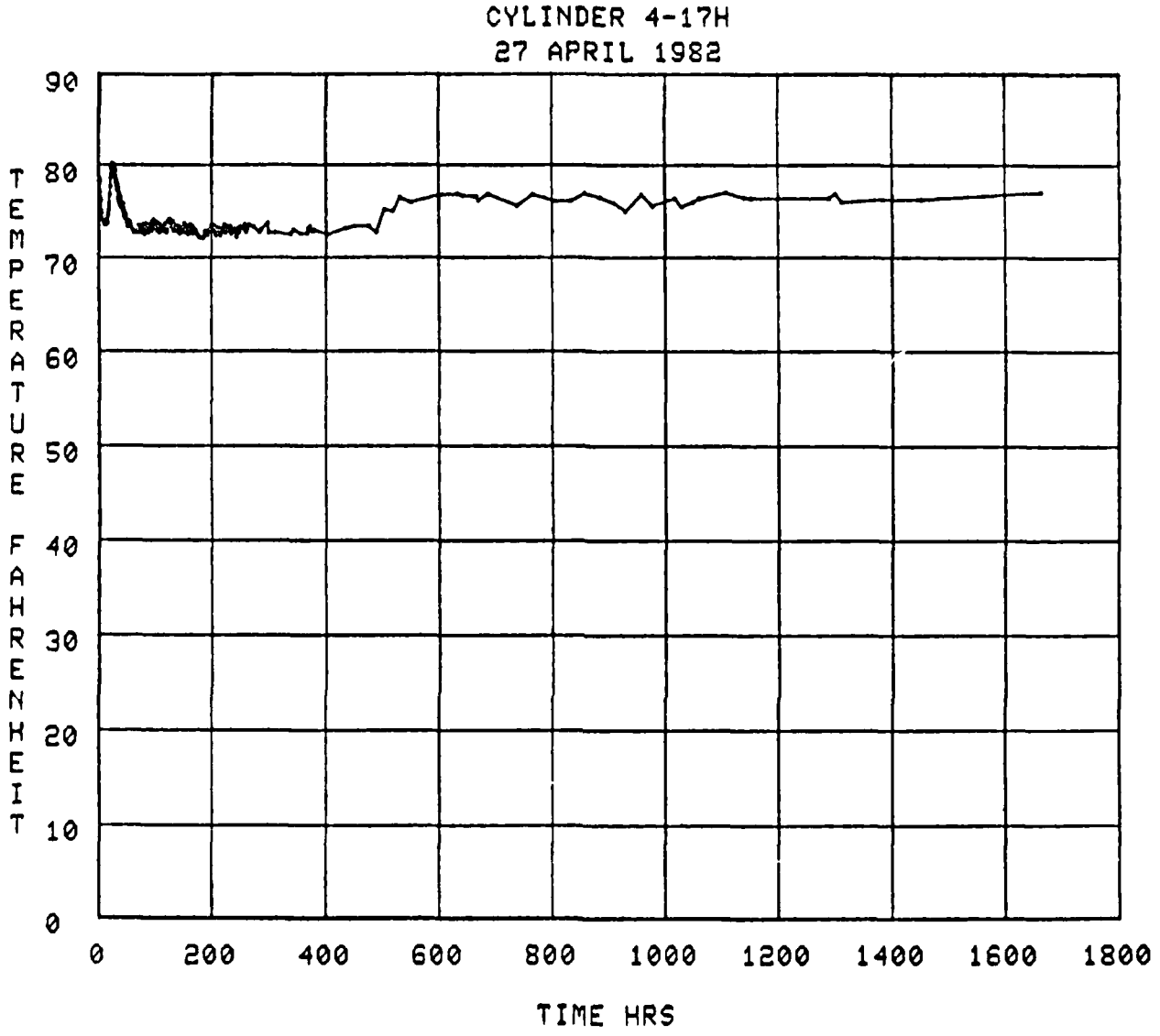
1400
1600
1800
TIME HRS


CYLINDER 4-17H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
90
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0
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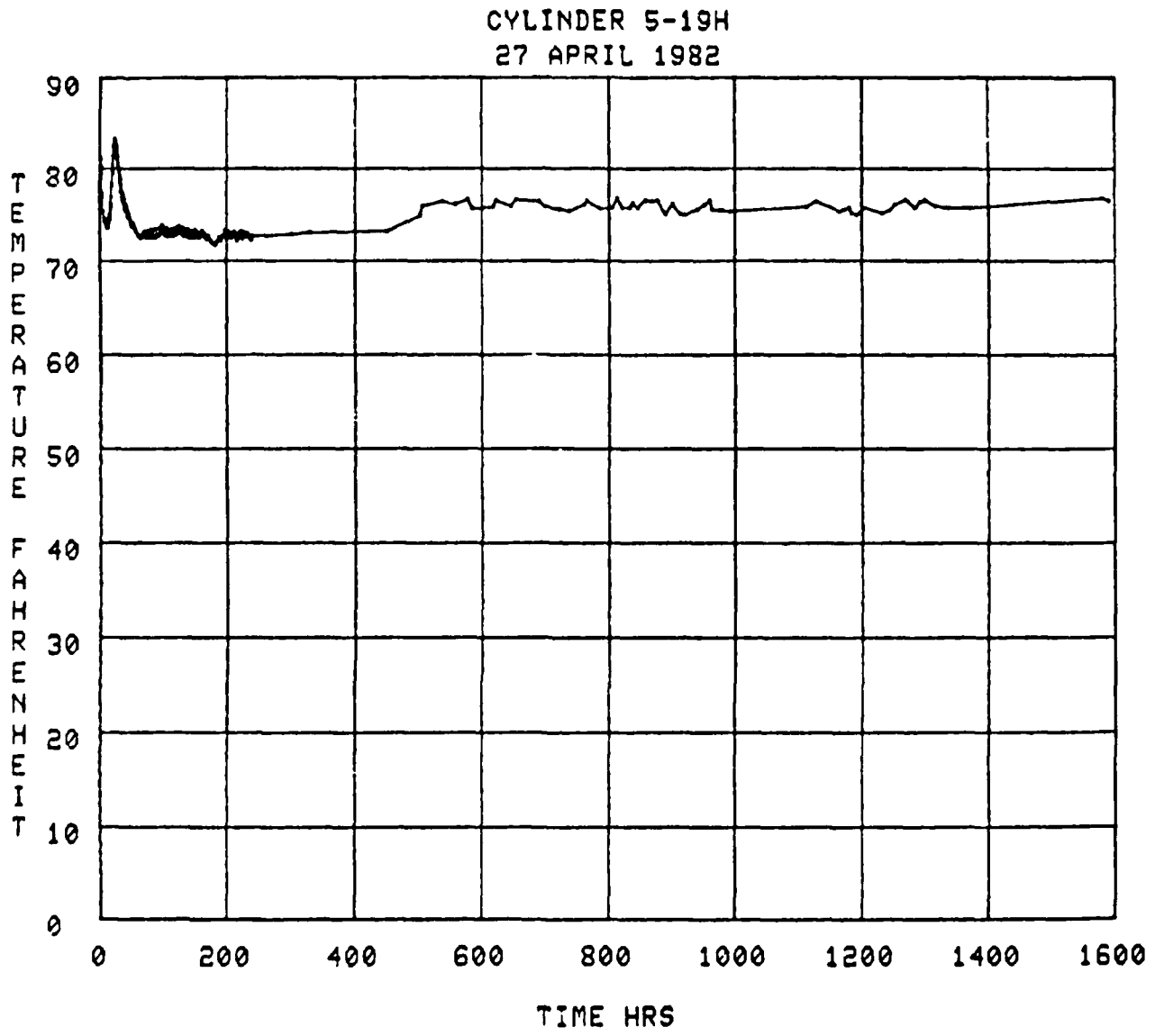
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 5-19H
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TEMPERATURE FAHRENHEIT
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30
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0
0
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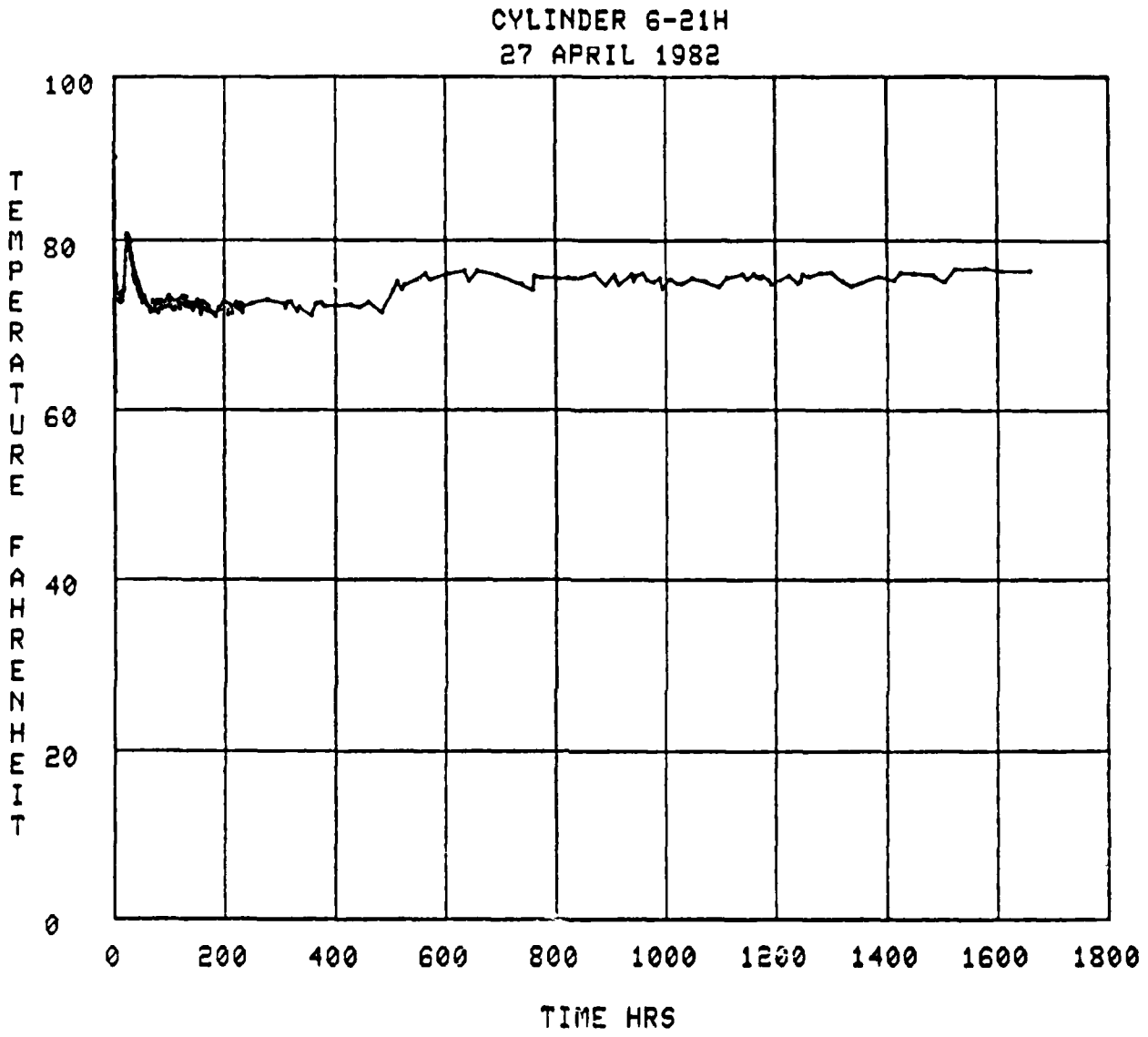
400
600
800
1000
1200
1400
1600
TIME HRS


CYLINDER 6-21H
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TEMPERATURE FAHRENHEIT
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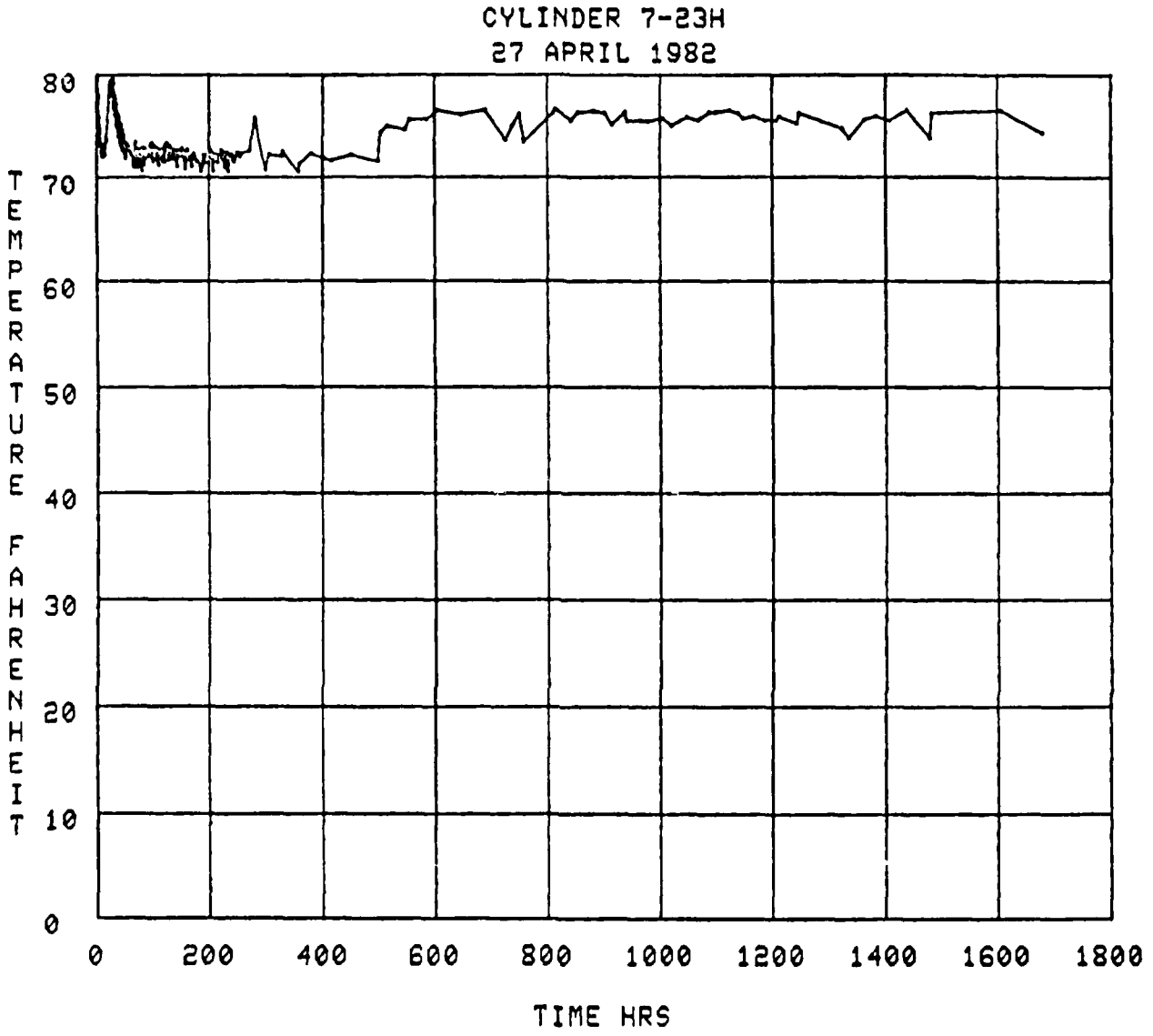
1600
1800
TIME HRS


CYLINDER 7-23H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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1400
1600
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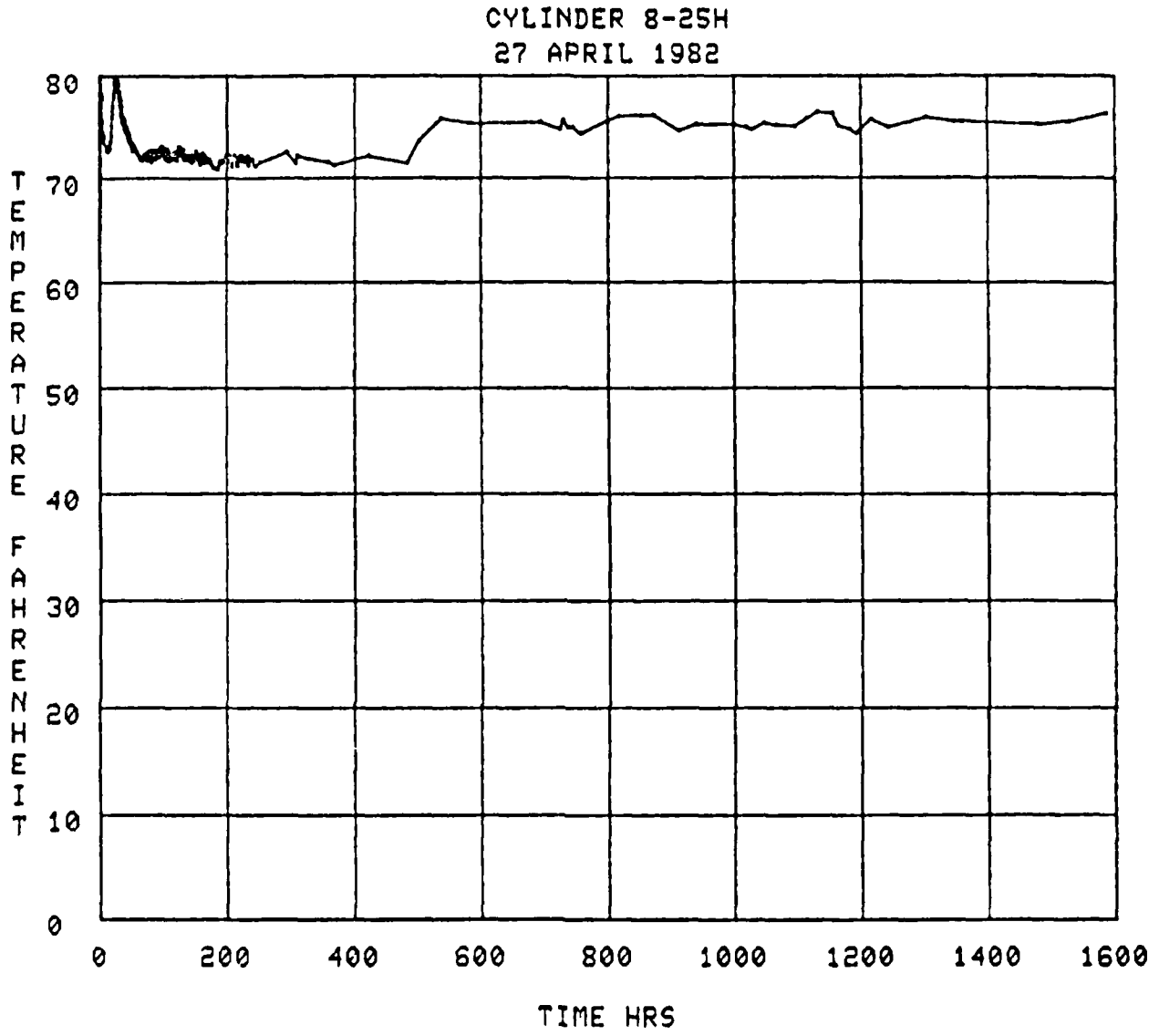
TIME HRS


CYLINDER 8-25H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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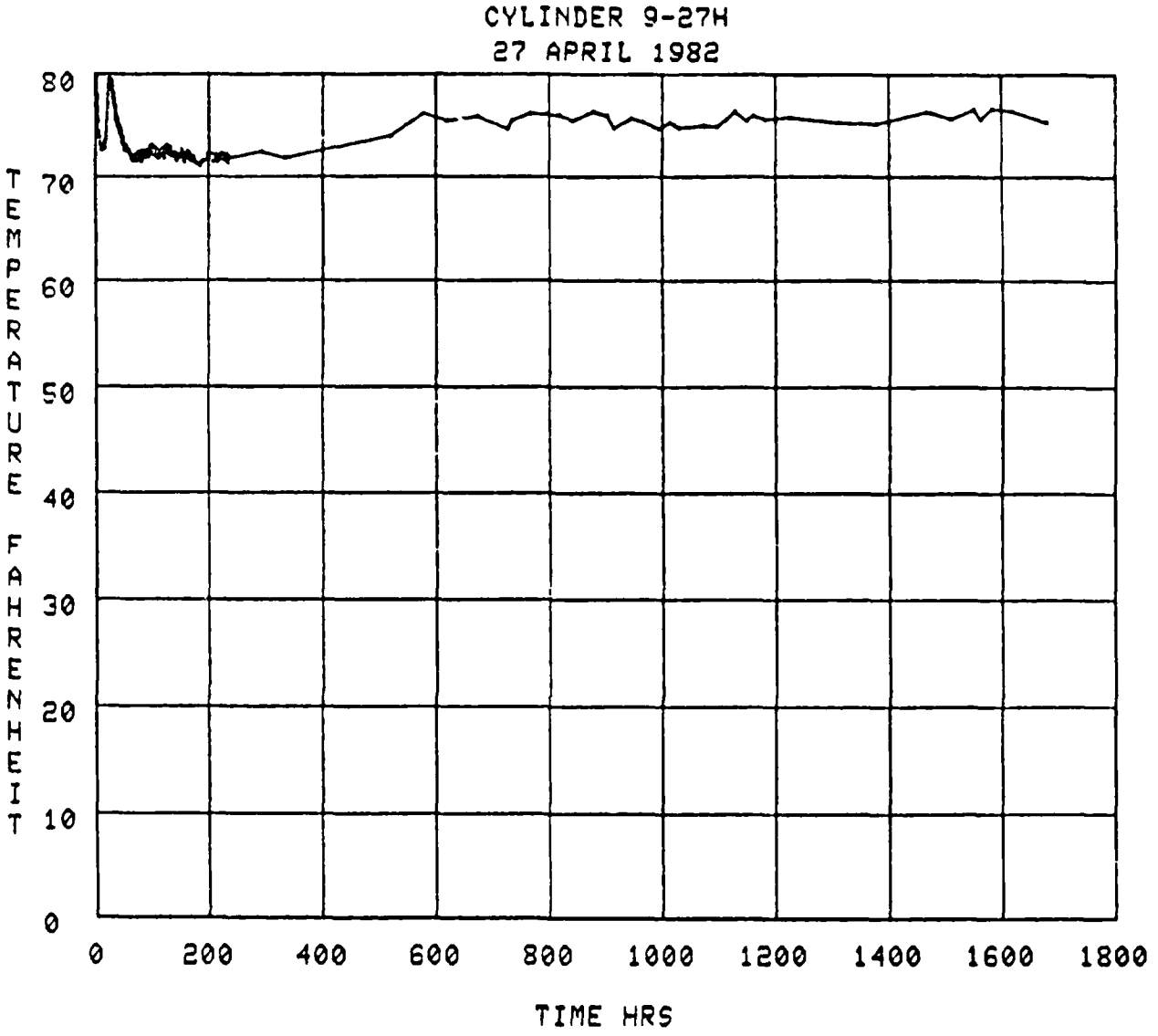
600
800
1000
1200
1400
1600
TIME HRS


CYLINDER 9-27H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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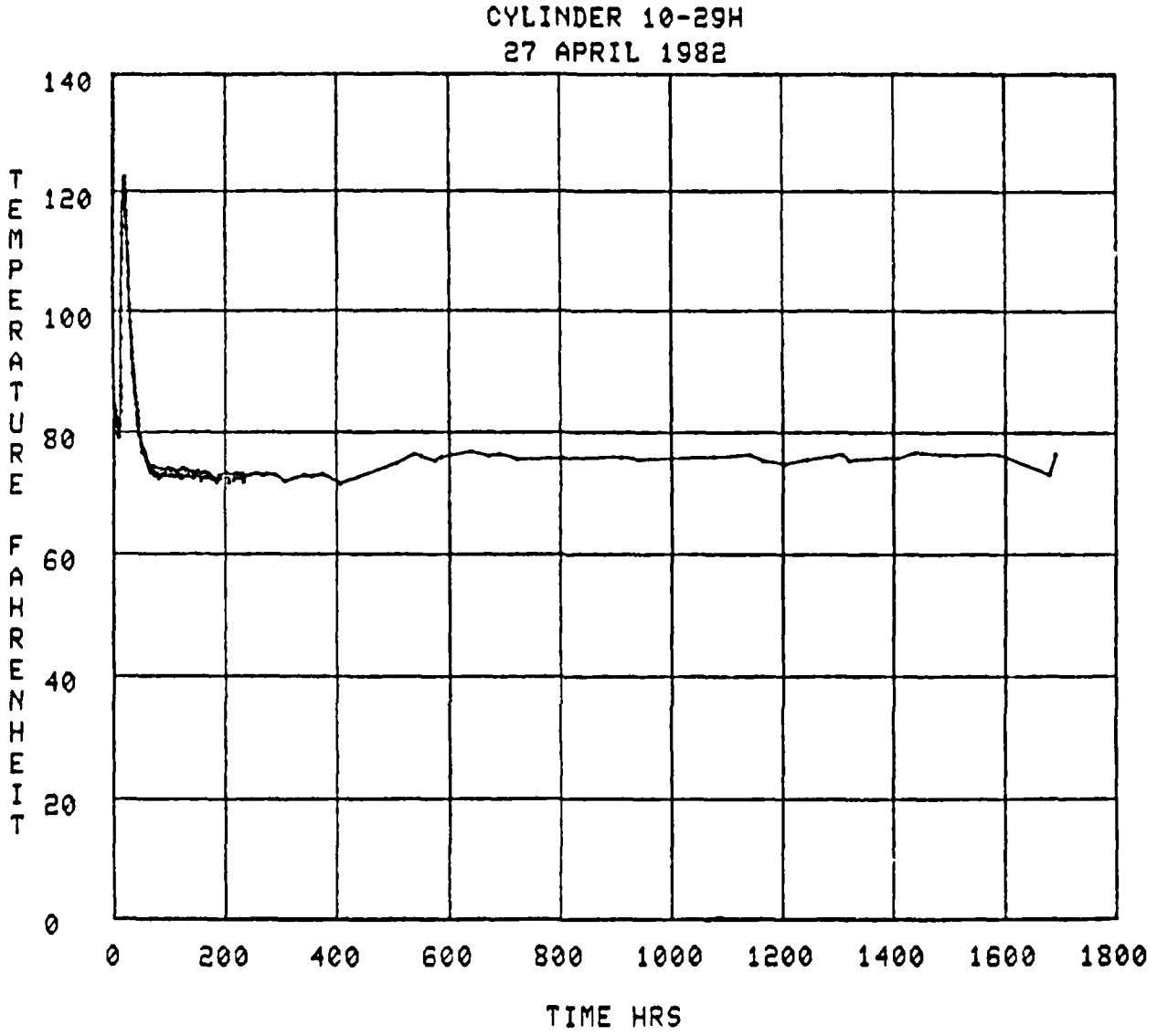
800
1000
1200
1400
1600
1800
TIME HRS


CYLINDER 10-29H
27 APRIL 1982
TEMPERATURE FAHRENHEIT
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120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
TIME HRS

APPENDIX F: NOTATION

A	Area
B	Intercept of straight line with y axis
d_p	Incremental change in radial distance
D	Diameter
E	Modulus of elasticity
E_B	Modulus of elasticity of grout bar, psi
f_B	Stress produced by grout bar, psi
F_f	Frictional stress
K	Pressure-strain relation
L	Cylinder length
m_1	Restraint due to hoop strain in a cylinder, $\frac{\text{psi}}{\text{in./in.}}$
M	Slope of straight line
p	Internal force or pressure
p_D	Interface pressure times cylinder diameter
p_h	Hoop pressure
p_1	Pressure on inside surface of pipe
p_r	Radial pressure
P_B	Restraining force of the grout bar
P_c	Force in the cylinder walls
P_f	Frictional force
P_ℓ	Longitudinal force
r	Radius
r_c	Radius of cylinder
r_1	Internal radius of cylinder, in.
r_2	External radius of cylinder, in.
R	Restraint of restraining environment
R_B	Grout bar restraint
R_c	Cylinder restraint
RST	Restrained grout bar
UNRST	Unrestrained grout bar
v	Volume
α	Linear expansion
β	Constant of integration
Δ	Incremental value
ε	Strain
ε_h	Hoop strain

ε_{hc}	Hoop strain at midheight on the cylinder surface
ε_{ℓ}	Longitudinal strain
ε_{t}	Tangential strain
μ	Poisson's ratio
ρ	Radial distance
σ	Stress
σ_{e_c}	Longitudinal equivalent fluid pressure stress produced in the cylinder, psi
σ_{R}	Stress produced by restraining rod in grout bar, psi

END

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